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ADAPTIVE ATTITUDE CONTROL COMPUTER
FOR
SPACECRAFT STABILIZATION

FINAL REPORT

MAY 1968

CONTRACT NO. NAS5-10423

Prepared by

GENERAL ELECTRIC COMPANY
AVIONIC CONTROLS DEPARTMENT
BINGHAMTON, NEW YORK

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GODDARD SPACE FLIGHT CENTER
GREENBELT, MARYLAND

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Goddard Space Flight Center

Technical Officer: C.C. Barrett

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for

Goddard Space Flight Center
Greenbelt, Maryland

ABSTRACT

This publication is the final report of the program for the design, fabrication, and feasibility demonstration of a breadboard model of a three-axis spacecraft Adaptive Attitude Control Computer. The work was performed by the Avionic Controls Department of the General Electric Company for the NASA Goddard Space Flight Center under Contract No. NAS5-10423. Included in this report is a description of the Adaptive Attitude Control Computer, performance data, theory of operation, and operating instructions. Schematic diagrams, assembly drawings, and parts lists are also included as a separate package.

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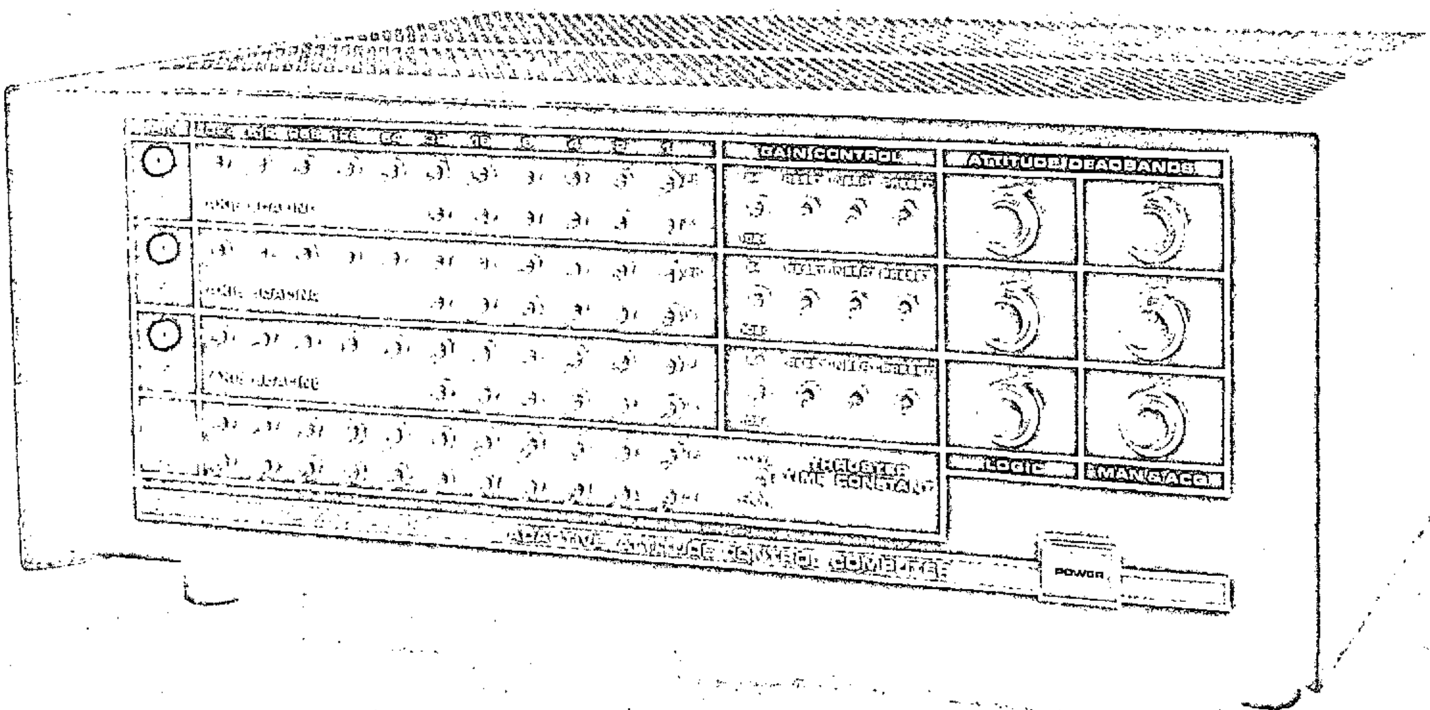


Figure 1. Adaptive Attitude Control Computer Breadboard

Which normally degrade the performance of reaction jet systems have no effect on the performance of the Adaptive Attitude Controller. Such changes (sometimes referred to as plant variations) are identified and compensation is made automatically within the controller. Optimum thruster on-times are computed digitally from measurements of time intervals between attitude threshold crossings within the angular deadband.

SUMMARY OF SYSTEM PERFORMANCE REQUIREMENTS

The following performance requirements were established by GSFC for the Adaptive Attitude Control Computer. Performance tests of the unit operating with an analog computer which simulates the attitude sensors, reaction jets, and three-axis spacecraft dynamics have shown that all requirements have been met.

RANGE OF NOMINAL PARAMETER SCALING

The three-axis adaptive control unit shall be adjustable for various satellite configurations and parameters. These parameters and ranges of variation are as follows:

a. Moments of Inertia - variable from 100 to 5000 slug ft^2 on any or all three axes.

b. Angular Deadband - variable from ± 0.1 to ± 1.0 degree on any or all three axes.

c. Control Torque Magnitude - shall range from ± 0.005 to ± 0.2 foot-pounds.

d. Thruster Rise and Decay Time Constants - variable up to 3.0 seconds, common to all three axes, with resolution to 1 percent. Thruster time constants are defined as τ_1 (rise) and τ_2 (decay) in the following equations for control torque (T_c).

$$T_c\ (\text{on}) = A\ (1 - e^{-t/T_1})$$

$$T_c\ (\text{off}) = A\ e^{-t/T_2}$$

where A is the control torque magnitude given in (c) above.

MODES OF OPERATION

a. Attitude Acquisition Mode - The controller shall demonstrate three-axis attitude acquisition for deadband entry rates consistent with the ranges of parameters given above. Vehicle rates shall then be reduced to achieve the optimum limit cycle trajectory within the attitude deadband.

b. Undisturbed Limit Cycle Mode - The undisturbed limit cycle mode shall be maintained when the external disturbance torque is near zero. This mode is achieved when each control pulse is the minimum deliverable by the control system.

c. Scalloped Operation Mode - The optimum limit cycle trajectory to be maintained in the presence of external disturbance torque is defined as a parabolic trajectory within the deadband (scallop) as illustrated in Figure 2. To minimize thruster cycling, the "depth" of these scallops shall be at least 75 percent of the control deadband.

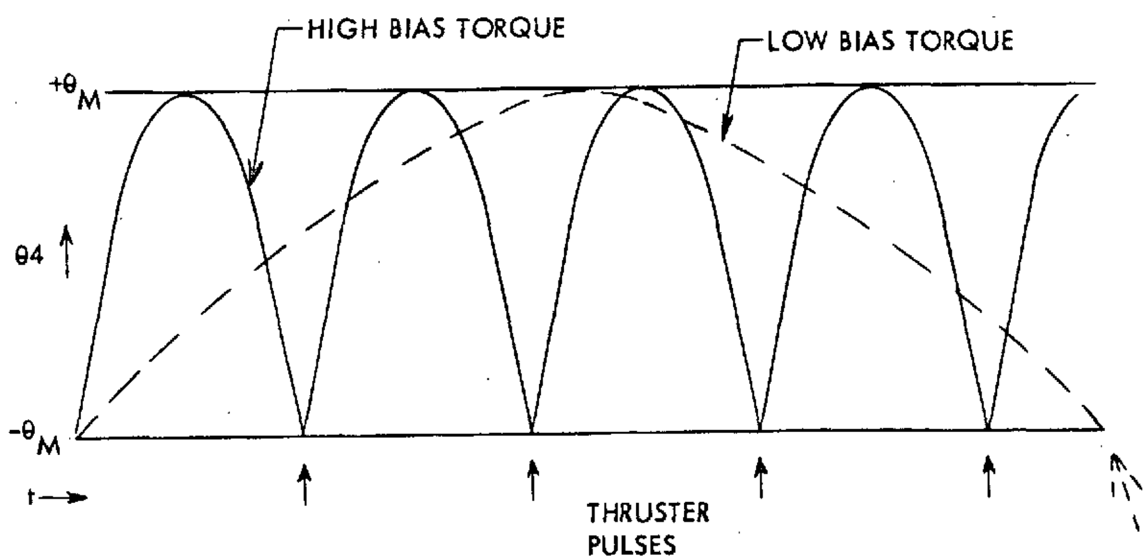


Figure 2. Optimum Vehicle Trajectories in a Bias Torque Environment

DISTURBANCE TORQUE AND PLANT CHANGES

For any specified set of control and vehicle parameters, optimum limit cycle performance shall be maintained over a disturbance torque range of $\pm 2.0 \times 10^{-4}$ ft-lb, steady-state thrust level degradation of 25 percent, and thruster misalignments of 1^{o}.

SENSOR CHARACTERISTICS

Performance shall not be adversely affected by the following sensor characteristics:

a. Signal-to-noise ratio of five-to-one (white noise).

b. Uncertainty of electrical null equal to $\pm$ 0.008 degree.

c. Cross-coupling of $\pm$ 0.025 degree maximum over a full linear range of $\pm$ 0.5 degree.

GENERAL DESCRIPTION OF THE ADAPTIVE ATTITUDE CONTROL COMPUTER

A single axis block diagram of the Adaptive Attitude Control Computer and simulated sensor, thrusters, and spacecraft dynamics is shown in Figure 3. The interface signals of the three-axis unit consist of the following.

- Three attitude sensor inputs (one per axis)

  $\theta_x, \theta_y, \theta_z$

  Sensor Gradient: 25 v/degree

- Six thruster on-time command signals (two per axis, plus and minus)

  $\pm t_{on_x}, \pm t_{on_y}, \pm t_{on_z}$

  Zero to +5 vdc

- +28 vdc power

  48 watts (exclusive of power supply inefficiency)

Parameter scaling for the specified satellite configurations and control system parameters is made by means of front panel switching and potentiometer adjustments. Computer scaling and operating instructions are included in Section III of this report.

The electronic circuitry of the Adaptive Attitude Control Computer consists largely of microelectronic Sylvania Universal High Level Logic (SUHL) transistor-transistor elements with discrete components used where necessary. The electronics are mounted on 25 pluggable boards, and packaged to provide maximum convenience and accessibility for laboratory operation. Power converters are mounted directly behind the front panel to convert 28 vdc to ± 12 vdc and +4.8 vdc. A complete set of assembly drawings and schematics are provided with this report as a separate package.

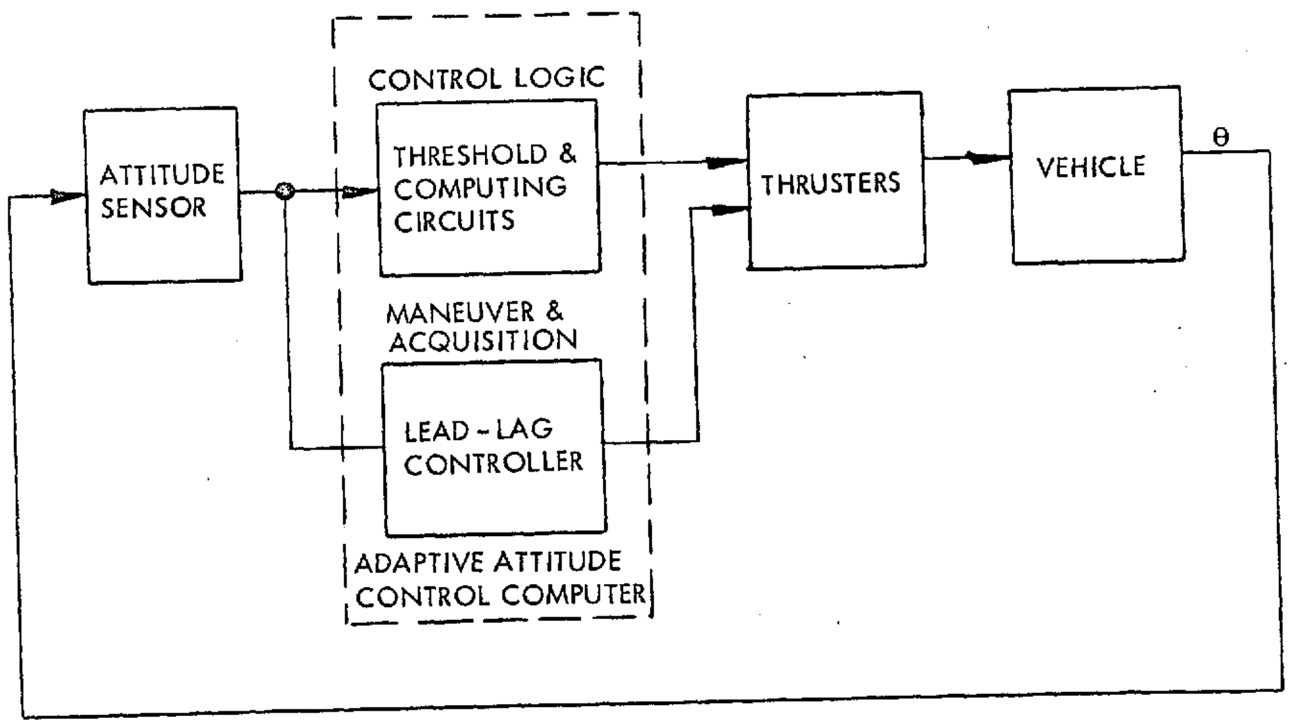


Figure 3. Block Diagram of the Adaptive Attitude Control Computer and Simulated Sensor, Thruster and Vehicle

SECTION II

SYSTEM PERFORMANCE DATA

Some typical results of system evaluation test runs of the Adaptive Attitude Control Computer are shown on the following pages. Performance is illustrated under various conditions of initial rates, thruster time constants, bias torques, moments of inertias, angular deadbands, control torque levels, and plant variations.

For those test runs where limit cycle acquisition is shown, the initial ratio of control torque-to-moment of inertia ratio for each axis is nominally set to ≈ 5 percent accuracy. The computer is then allowed to acquire the limit cycle and adjust its own gain to the actual value. Such a condition is considered to be a realistic representation of flight system accuracy. In all cases, a sensor signal-to-rms noise level of five-to-one is employed. In every case, the optimum limit cycle is acquired.

Figure 4 illustrates the acquisition of the optimum limit cycle from an initial rate of 10^{-3} rad/sec. The vehicle moment of inertia is 1000 slug-ft^2, with an angular deadband of $\pm 0.1^{\circ}$. The bias torque level is 2×10^{-4} ft-lb. The control torque is 0.019 ft-lb, with the thruster rise time constant 0.1 second, and the fall time constant 0.5 second.

Figures 5 and 6 show computer performance under a wide range of system parameters and environmental conditions.

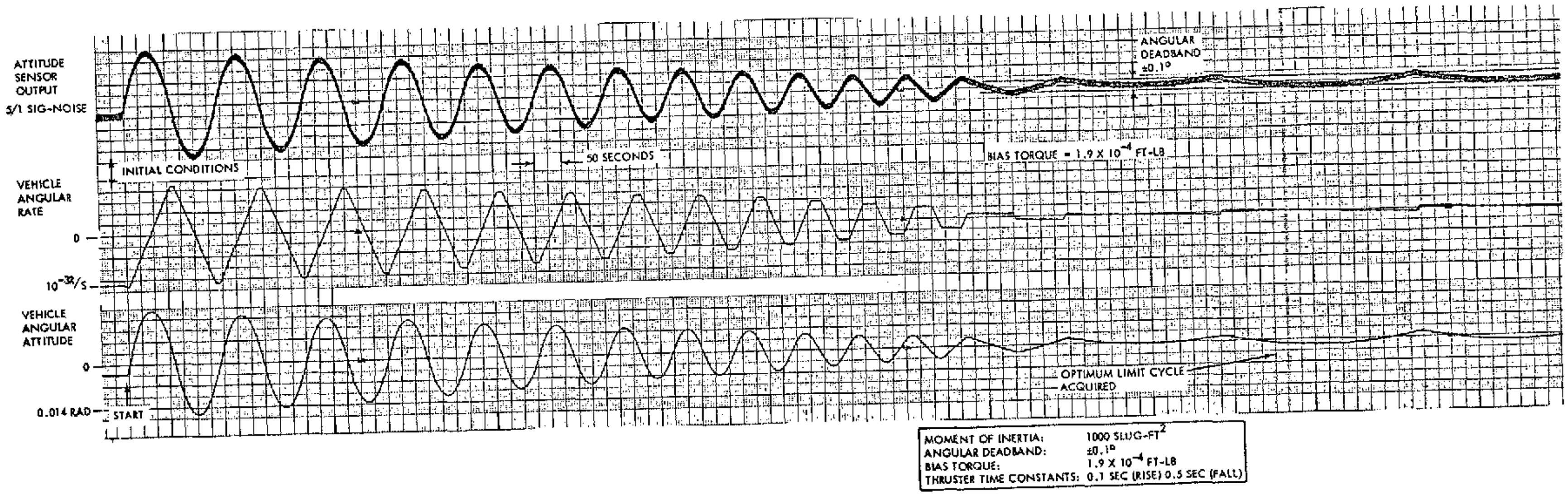


Figure 4. Optimum Limit Cycle Acquisition From High Initial Vehicle Angular Rate (10^{-3} rad/sec)

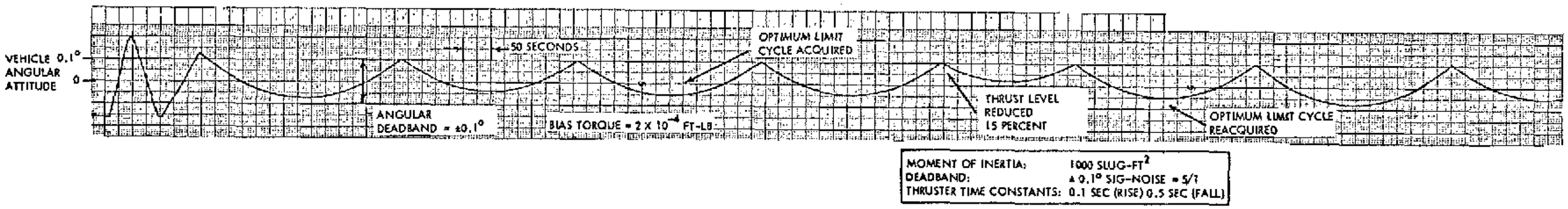


Figure 5A. Initial Acquisition of Optimum Limit Cycle, Then Re-acquisition After a 15 Percent (Step) Degradation in Thrust Level.

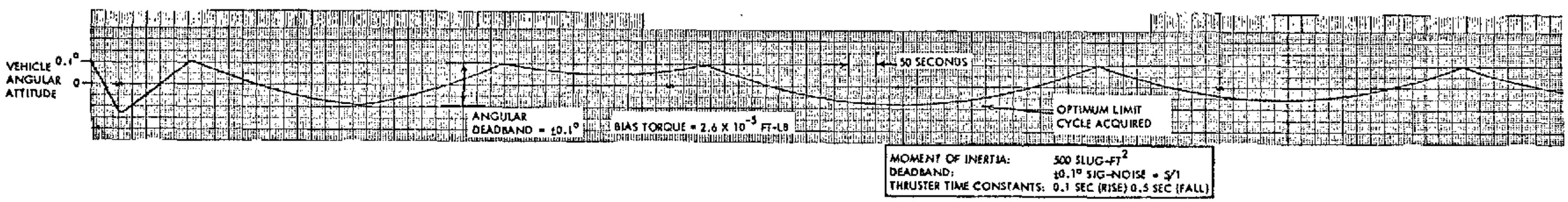
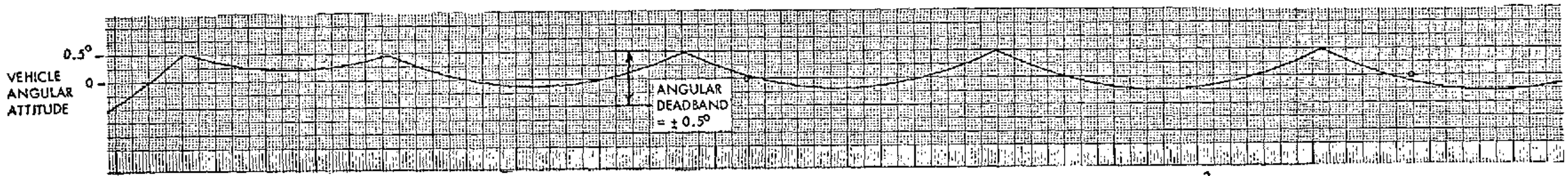
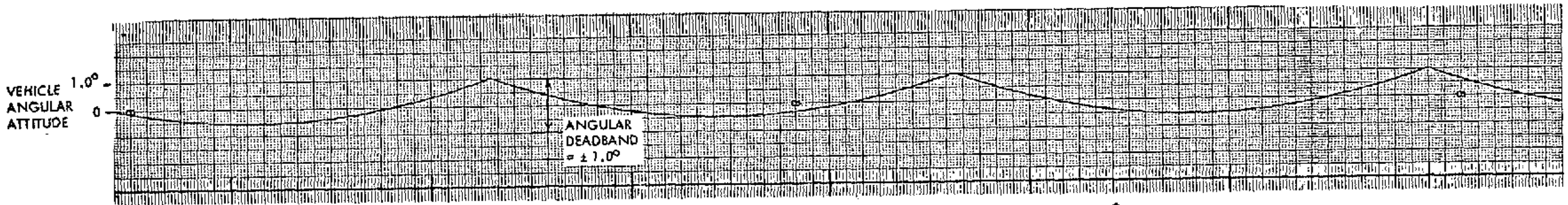


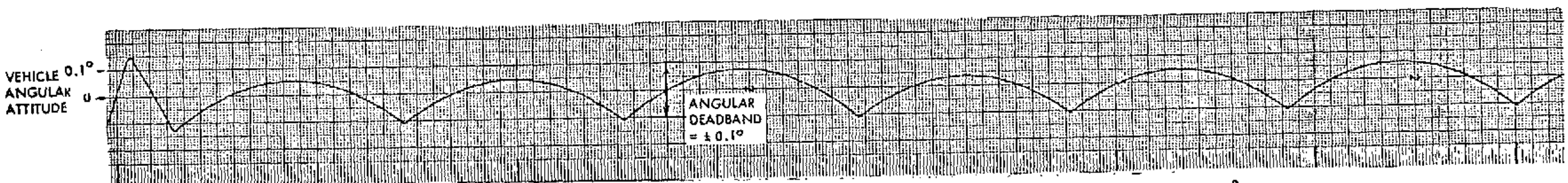
Figure 5B. Acquisition of Optimum Limit Cycle in Bias Torque Environment of 2.6 x 10^{-5} ft-lb.



OPTIMUM LIMIT CYCLE ACQUISITION. ANGULAR DEADBAND ± 0.5°, MOMENT OF INERTIA 500 SLUG-FT^2
THRUSTER TIME CONSTANTS 0.1 SEC (RISE) 0.5 SEC (FALL),
BIAS TORQUE 2.2 X 10^{-4} FT-LB SIG-NOISE 5/1.



OPTIMUM LIMIT CYCLE. ANGULAR DEADBAND ±1.0°, MOMENT OF INERTIA 100 SLUG-FT^2,
THRUSTER TIME CONSTANTS 0.5 SEC (RISE) 0.1 SEC (FALL),
BIAS TORQUE 4.3 X 10^{-5} FT-LB SIG-NOISE 5/1.



OPTIMUM LIMIT CYCLE ACQUISITION. ANGULAR DEADBAND ±0.1°, MOMENT OF INERTIA 500 SLUG-FT^2
THRUSTER TIME CONSTANTS 0.1 SEC(RISE) 0.5 SEC (FALL)
BIAS TORQUE 10^{-4} FT-LB, SIG-NOISE 5/1.

Figure 6. Typical Performance of the Adaptive Attitude Control Computer. Chart Speed 0.2 MM/Sec.

SECTION III

DESCRIPTION OF THE ADAPTIVE ATTITUDE CONTROL COMPUTER

CONTROL THEORY

The Adaptive Attitude Control Computer is designed to provide optimum controller performance when the external bias torque is constant (slowly changing) or zero. It is effective over a wide range of external bias torque. Its application to the problem of spacecraft attitude control allows fuel efficiency to approach the theoretical maximum, while also minimizing the frequency (and therefore the total number) of control torque impulses for a given mission.

To maximize the time between thruster actuations and fuel efficiency, the control objective must be to produce a parabolic vehicle attitude trajectory within the deadband which does not require a return thrust pulse. The depth of this trajectory should penetrate to a point very near the opposite side of the attitude deadband (see Figure 7). This trajectory depth (or amplitude) is shown in Figure 7 to reach within an angle of θ_G of the opposite side of the deadband, and must be maintained over a specified range of bias torque acting on the vehicle. The parabolic trajectories for a constant bias torque are symmetrical, and their amplitudes depend on the initial vehicle rate at the deadband limit ($\pm\theta_M$) and the existing bias acceleration. The trajectory is described by the equation:

$$\frac{d\omega}{dt} = -\alpha_o \tag{1}$$

where $\omega = \frac{d\theta}{dt}$

θ = vehicle angular position

α_o = vehicle acceleration

This equation can be re-arranged to obtain the relationship between the optimum depth of the parabola, required initial vehicle rate at the deadband limit (ω_c) and bias acceleration (α_B).

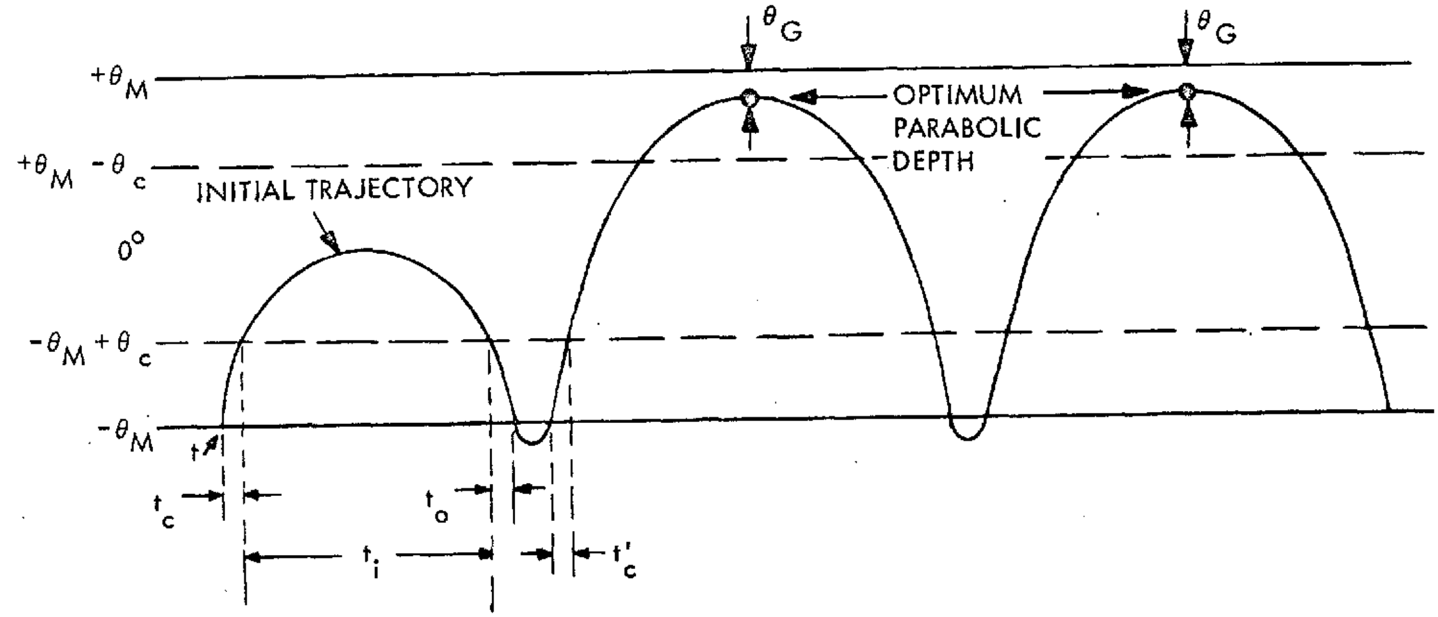


Figure 7. Optimum Limit Cycle Trajectory Acquisition and Time Intervals Used for Thruster On-Time Computation

$$\frac{d\omega}{d\theta}\ \frac{d\theta}{dt} = -\alpha_B \tag{2}$$

$$\frac{d\omega}{d\theta}\ (\omega) = -\alpha_B$$

$$\omega d\omega = -\alpha_B\ d\theta$$

$$\int_{\omega_c}^{o} \omega d\omega = -\int_{-\theta_M}^{\theta_M - \theta_G} \alpha_B\, d\theta$$

$$\omega_c = 2 \left[\alpha_B \left(\theta_M - \frac{\theta_G}{2}\right)\right]^{1/2}$$

This is the vehicle rate required at the deadband limit (as a result of a thrust pulse) to obtain an optimum vehicle trajectory. The thruster on-time required (t_{on}) is:

$$t_{on} = \frac{\omega_o + \omega_c}{\alpha_c} \tag{3}$$

where ω_o = instantaneous vehicle rate preceding initiation of the thrust pulse

ω_c = instantaneous vehicle rate at the end of the thrust pulse

α_c = net control torque
(Thrust x moment arm - α_B)

or

$$t_{on} = \frac{1}{\alpha_c} \left\{ 2 \left[\alpha_b \left(\theta_M - \frac{\theta_G}{2}\right)\right]^{1/2} + \omega_o \right\} \tag{4}$$

Equations (3) and (4) are therefore general expressions for the duration of a control torque impulse which will effect an optimal limit cycle trajectory in a constant bias torque environment. In these equations, the term α_c, control acceleration, may be considered as the "plant" constant. This constant is the ratio of control torque to vehicle moment of inertia T_C/I_V, and therefore is affected by variations of the internal control system parameters (plant). If any variations within the plant occur for example, thrust level, vehicle moment of inertia, center of mass, or thruster misalignment, the plant constant α_c will vary. In this event, equations (3) and (4) will no longer represent an expression for thrust impulse duration to achieve an optimum limit cycle trajectory.

In order to achieve self-adaptive capability, the plant constant must be recomputed after each optimal thrust impulse. This is accomplished by measuring vehicle rate after the thruster impulse and using the equation

$$\omega_{cm} = \alpha'_c t_{on} - \omega_o \tag{5}$$

or

$$\alpha'_c = \frac{\omega_{cm} + \omega_o}{t_{on}}$$

where

ω_{cm} is the measured rate following the thruster impulse

α'_c is the newly-computed control acceleration (plant constant)

The control technique requires that vehicle rate (ω_o) at the attitude deadband limit, and the constant bias acceleration (α_B) be obtained for the computation of the optimal thrust impulse duration (t_{on}). The double-threshold time interval mechanization has been selected for this purpose. For the purposes of development, it will be assumed that the initial vehicle trajectory within the attitude deadband after the last acquisition pulse is a parabola within $\pm\theta_M$. (Refer to Figure 7). This trajectory is described by the equation

$$\theta(t) = -\theta_M + \omega_o t - \frac{\alpha_B t^2}{2} \tag{6}$$

The two intersections with the threshold $\theta = (-\theta_M + \theta_c)$ yield the equations

$$\theta_c = \omega_o t_o - \frac{\alpha_B t_o^2}{2} \tag{7}$$

$$\theta_c = \omega_o (t_o + t_i) - \alpha_B \frac{(t_o + t_i)^2}{2} \tag{8}$$

(where it is assumed that bias acceleration α_B is constant and therefore $t_c = t_o$)

Equations (7) and (8) can be solved simultaneously for α_B and ω_o.

$$\alpha_B = \frac{2\theta_c}{t_o(t_o + t_i)} \tag{9}$$

$$\omega_o = \frac{\theta_c(t_i + 2t_o)}{t_o(t_o + t_i)} \tag{10}$$

Equations (9) and (10) provide the measured values of ω_o and α_B used in the computation of the optimal t_{on}. If the optimum depth of the parabolic trajectory is chosen to be $2\theta_M - \theta_G$ as shown in Figure 7, then

$$t_{on} = \frac{1}{\alpha_c}\left\{2\left[\alpha_B\left(\theta_M - \frac{\theta_G}{2}\right)\right]^{1/2} + \omega_o\right\} \tag{11}$$

or

$$t_{on} = \frac{1}{\alpha_c}\left\{2\left[\frac{2\theta_c\left(\theta_M - \frac{\theta_G}{2}\right)}{t_o(t_i + t_o)}\right]^{1/2} + \frac{\theta_c(t_i + 2t_o)}{t_o(t_i + t_o)}\right\} \tag{12}$$

Equation (12) gives the expression for the duration of the thruster impulse to produce an optimal limit cycle trajectory in terms of angular constants, time intervals between threshold crossings, and the plant constant.

The time interval t_c, as shown in Figure 7, is used to compute a new value of control acceleration (plant constant α_c). After the thrust impulse, the expression for the vehicle trajectory is

$$\theta(t) = -\theta_M + \omega_{cm}t - \frac{\alpha_B t^2}{2} \tag{13}$$

where ω_{cm} is the vehicle rate at the end of the thrust impulse.

At $t = t_c$,

$$\theta_c = \omega_{cm} t_c - \frac{\alpha_B t_c^2}{2} \tag{14}$$

where

$$\omega_{cm} = \alpha'_c t_{on} - \omega_o \tag{15}$$

Substituting equation (15) into (14) and solving for α'_c gives

$$\alpha'_c = \frac{1}{t_{on}} \left[\omega_o + \frac{\theta_c}{t_c} + \frac{\alpha_B t_c}{2} \right] \tag{16}$$

$$\alpha'_c = \frac{\theta_c}{t_{on}} \left[\frac{t_i + 2t_o}{t_o (t_i + t_o)} + \frac{1}{t_c} + \frac{t_c}{t_o (t_i + t_o)} \right] \tag{17}$$

Equation (17) is an expression for the plant constant, α'_c, to be used in the computation of the next thruster on-time.

In the event that the attitude deadband is crossed and a return pulse is required to maintain attitude accuracy, the control technique employs an alternate equation for thruster on-time. This equation is designed to reduce the absolute value of vehicle angular momentum each time the deadband is crossed to a level where the return parabolic trajectory occurs, or the minimum impulse bit is reached (when bias torque is near zero). This alternate equation for t_{on} is given as

$$t_{on} = \frac{1.5}{\alpha_c} \frac{\theta_c}{t_o} \tag{18}$$

where α_c is the plant constant $\frac{T_c}{I_V}$ and θ_c and t_o are indicated in Figure 8.

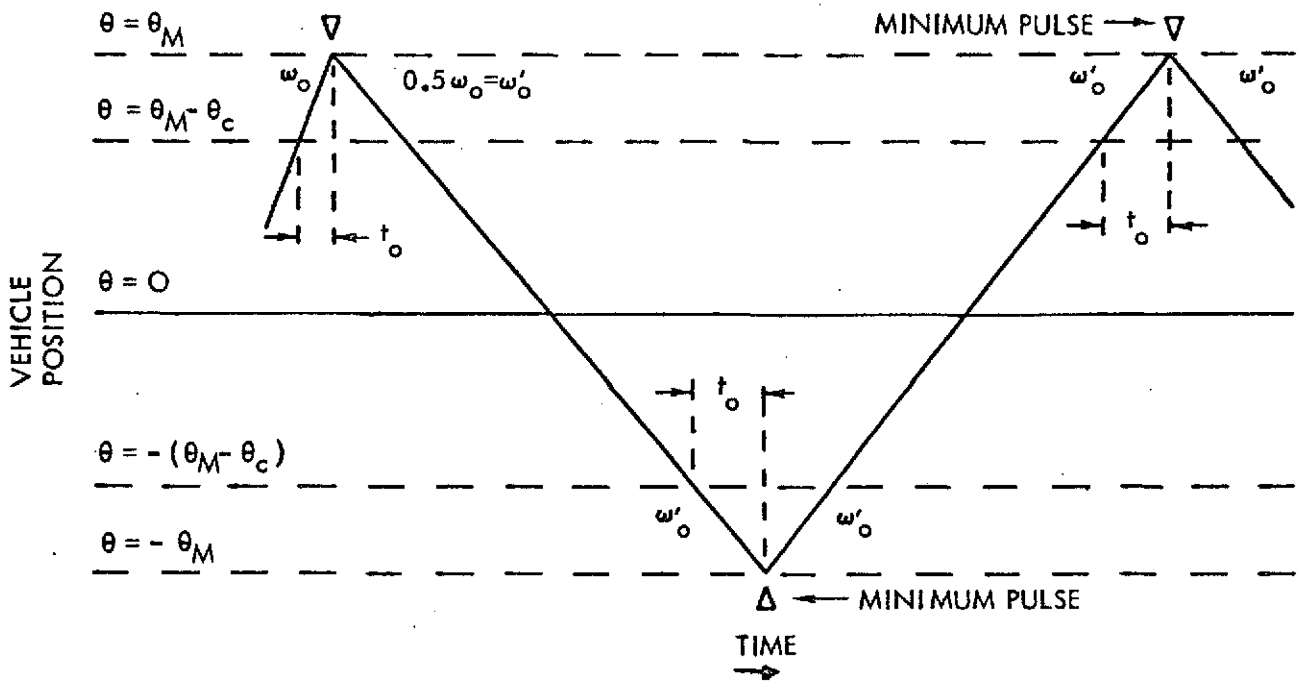


Figure 8. Effect of Alternate t_{on} Computation in Zero Bias Torque Environment

In a zero bias torque environment, this equation effectively reduces the absolute value of vehicle rate by a factor of 0.5 with each thruster impulse. In a bias torque environment greater than zero ($\alpha_B > 0$), successive deadband crossings and thrust impulses computed by this equation will result in an initial parabolic trajectory such as that generally assumed in Figure 7. At this point, the optimal t_{on} equation (equation 12) is employed. New computations of α_c' are made only after the occurrences of thrust pulses computed by Equation (12). The use of the alternate t_{on} equation (18) may therefore be considered the control equation for "scallop acquisition" and also as the control equation to achieve minimum-pulse operation in a zero bias torque environment.

The control theory and equations discussed essentially constitute the limit cycle control law of the Adaptive Attitude controller developed by the Avionic Controls Department. To provide a simple attitude limit cycle acquisition capability from relatively high attitude and/or rate errors to provide maneuver capability, and to assure limit cycle re-acquisition capability in the event of impulsive disturbance accelerations, a parallel lead-lag electronics subsystem is operated as a "maneuver and acquisition branch" with the computation electronics (refer to Single-Axis Block Diagram, Figure 9).

A simplified block diagram of a single-axis lead-lag subsystem is shown in Figure 10.

The nominal transfer function $\left(\frac{e_o}{e_i}\right)$ is given as

$$\frac{e_o}{e_i} = K_1 \left[\frac{\left(T_1 + \frac{K_2}{K_1}\right)}{(T_1 S + 1)} (S+1) \right] \qquad (19)$$

The ratio gains $\frac{K_2}{K_1}$, the lag time constant T_1, and threshold hysteresis may be set to insure limit cycle acquisition by choosing these values to effect a minimum thrust pulse large enough so the resulting attitude trajectory penetrates the inner threshold level of the electronics under worst-case high bias acceleration conditions.

An exponentially-decaying hysteresis signal is employed in the lead-lag subsystem to provide control of the minimum impulse bit in the limit cycle. This type of hysteresis also removes the possibility of multiple-pulsing due to sensor noise. Where long thruster on-times are employed (during maneuvers or limit acquisition

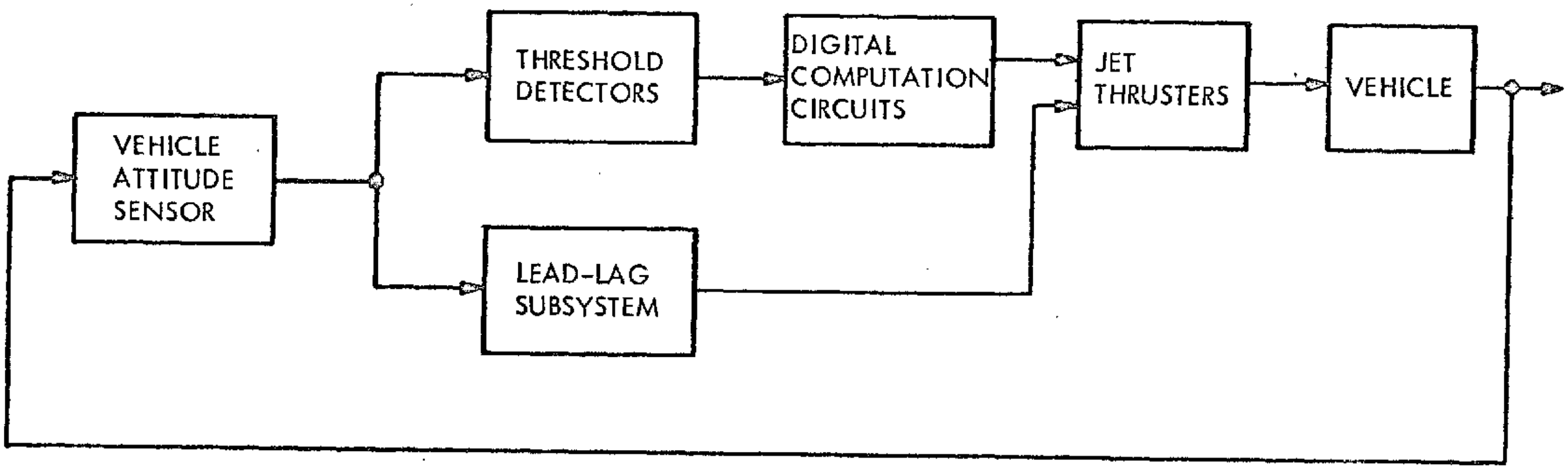


Figure 9. Block Diagram of Adaptive Attitude Control System

from high vehicle rates) the hysteresis effect decays to near zero. The time constant of this circuit is nominally set at two seconds. A trim pot adjustment of the magnitude of K_3 is provided in the Adaptive Attitude Control Computer.

A phase-plane diagram of a typical acquisition sequence in a bias torque condition is shown in Figure 11, with sequential on-off occurrences numbered chronologically. The last pulse results in optimal limit cycle acquisition.

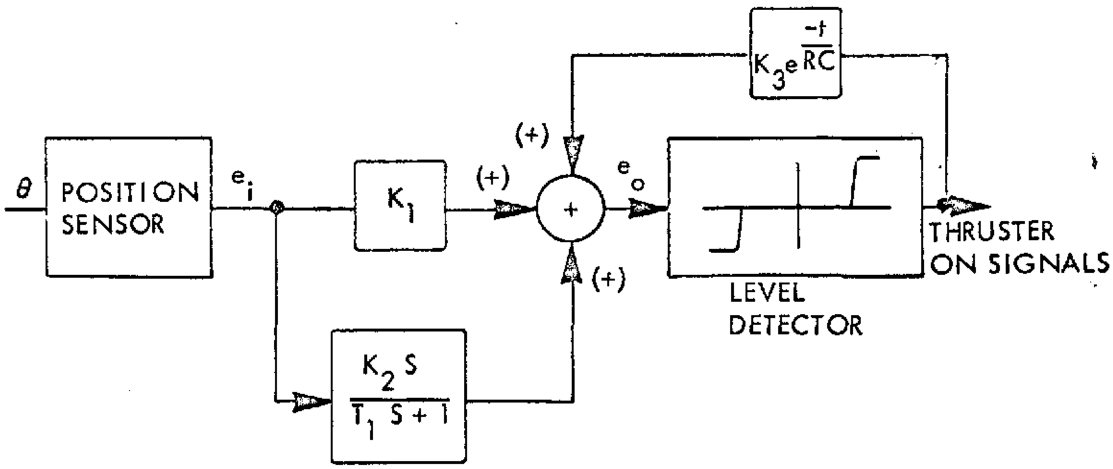


Figure 10. Single Axis Block Diagram of Lead-Lag

To summarize the above discussion, a single axis self-optimizing and adaptive control breadboard consists of the following equation mechanizations

$$t_{on} = \frac{1}{\alpha_c'} \left\{ 2 \left[\frac{2\theta_c (\theta_M - \frac{\theta_c}{2})}{t_o (t_i + t_o)} \right]^{1/2} + \frac{\theta_c (t_i + 2t_o)}{t_o (t_i + t_o)} \right\} \tag{20}$$

$$\alpha_c' = \frac{\theta_c}{t_{on}} \left[\frac{t_i + 2t_o}{t_o (t_i + t_o)} + \frac{1}{t_c} + \frac{t_c}{t_o (t_i + t_o)} \right] \tag{21}$$

These equations are identified as "parabolic mode" computations.

$$t_{on} = \frac{1.5}{\alpha_c} \quad \frac{\theta_c}{t_o} \tag{22}$$

This equation is identified as the "Standard Computation Mode".

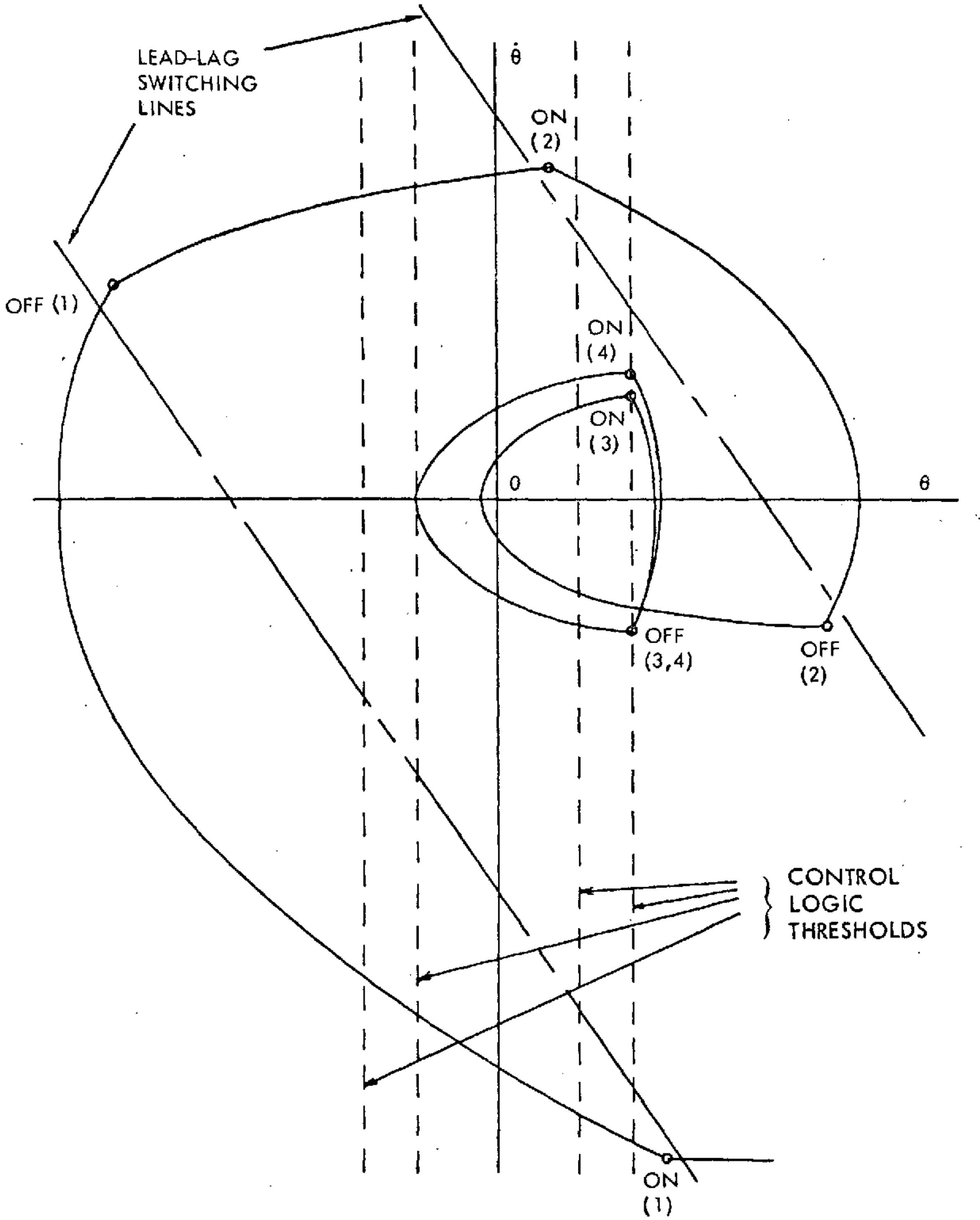


Figure 11. Typical Limit-Cycle Acquisition Sequence, Lead-Lag Optimum Pulse

A summary of computational events occuring within the computer is as follows:

(a) With initial penetration of deadband, time interval measurements begin. Measure t_i, t_o.

(b) If deadband is crossed, compute t_{on} based on standard mode equation. If return parabolic trajectory occurs, compute t_{on} based on Parabolic Mode Equation.

(c) After pulse is fired, measure to interval from end of t_{on} command to inner deadband penetration, (t_c).

(d) Compute new plant constant.

(e) Revert to (b).

Computation of a new plant constant is inhibited in the Adaptive Attitude Control computer under conditions where one or more of the measured variables (time intervals) in equation (21) exceed the scaled counter(s) range.

The preceding discussion of control theory is based on the assumption that the control torque impulse is approximated as a square wave. With the GSFC requirement that the thruster characteristics be defined by the equations

$$T_c \text{ on} = A(1 - e^{-t/\tau_1}) \tag{23}$$

$$T_c \text{ off} = A(e^{-t/\tau_2}) \tag{24}$$

where T_c = control torque

A = control torque magnitude

τ_1 = thruster rise time constant

τ_2 = thruster fall time constant

τ_1 and τ_2 variable to three seconds a correction must be made to the optimum thruster on time computed by equation (20). This correction involves the addition or subtraction of a constant value (depending on the polarity and magnitude of $T_2 - T_1$) from the computed on-time.

Using equations (23) and (24) to characterize the shape of the control torque impulse, the effective angular momentum (ft-lb-sec) imparted to the vehicle is the sum of the integrals of the above expressions, to

$$H_i = \int_0^{t_o} A\left(1 - e^{-t/T_1}\right) dt + \int_{t_o}^{\infty} A e^{\frac{-(t - t_o)}{T_2}} dt \tag{25}$$

where H_i is the angular momentum imparted to the vehicle by the control torque impulse, control torque (A) is >> external bias torque, and t_o is the interval between the occurrences of the "on" and "off" commands to the thruster (refer to Figure 12).

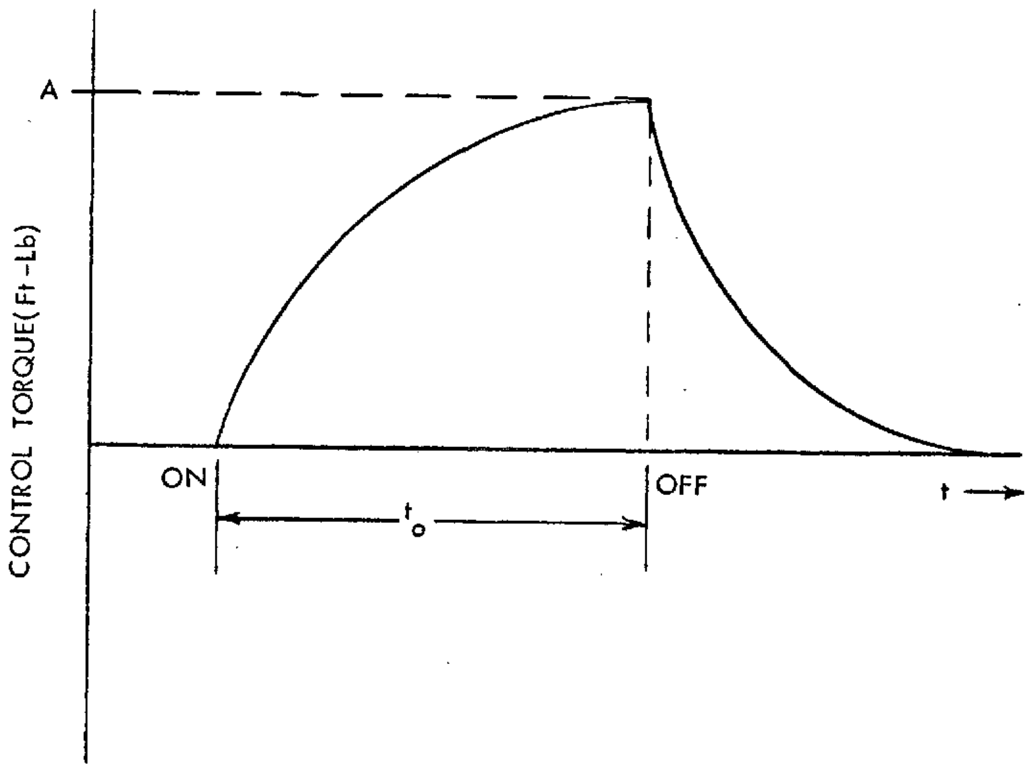


Figure 12. Control Torque Impulse

Performing the integrations shown, and grouping terms gives

$$* \quad H_i = At_o + A(T_2 - T_1) + A\,T_1 e^{-t_o/T_1} \tag{26}$$

Because of the fact that the specific impulse of a gas system degrades appreciably if the thruster is commanded on for an interval less than three times its "turn on" time constant (T_1), it is assumed that $t_o \geq 3T_1$ in order to preserve specific impulse efficiency. With this assumption, the term $e^{-t_o/T_1} \approx 0$, and equation (26) simplifies to

$$H_i \approx At_o + A(T_2 - T_1) \tag{27}$$

The required correction to the thruster on-time computed by equation (20) is therefore a constant value proportional to $T_2 - T_1$. The resulting output command from the Adaptive Attitude Control Computer is termed the "effective on-time" and is given by the equation

$$t_{on}\ \text{effective} = t_{on} - K = t_{on} - (T_2 - T_1) \tag{28}$$

Where t_{on} is the thruster on-time given by equation (20) selection of the magnitude and polarity of $(T_2 - T_1)$ is made on the front panel of the computer as discussed in the operating instructions section of this report.

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*Wells, R.C. - "A Study of Non-Linearities in Attitude Control Systems for Space Vehicles" - page 12. (Master's Thesis)

ELECTRONIC MECHANIZATION

The Adaptive Attitude Control Computer has two parallel control branches which are termed the Maneuver and Acquisition branch, and the Control Logic branch. The Maneuver and Acquisition branch is the analog lead-lag circuit. The reaction jet firing time is derived by the circuit in accordance with the following equation

$$T_{on} = f\left[K(\theta + \dot{\theta})\right]$$

The Control Logic branch is mechanized by analog attitude threshold circuits and digital computation circuits. This mechanization is discussed in detail in this Section.

The functional block diagram of one axis of the Adaptive Attitude Control Computer interfaced with an analog simulation is shown by Figure 13. The analog vehicle attitude signal (θ_x) is supplied at the input of the Control Logic branch and the Maneuver and Acquisition branch threshold circuits. The Control Logic branch controls the thruster on-time when the vehicle is limit cycling within the Control Logic threshold. If the vehicle attitude, position and rate, exceed the capability of the Control Logic branch, the Maneuver and Acquisition branch controls the thruster on time. This condition normally occurs during the acquisition portion of the mission when the vehicle attitude and rates are large.

MANEUVER AND ACQUISITION (LEAD-LAG) ELECTRONICS

The functional block diagram of the lead-lag electronic subsystem is shown in Figure 14. As seen from this figure, the controlling transfer function is

$$\frac{e_a}{e_\theta} = \frac{G_1\left(\frac{S}{0.6} + 1\right)}{\left(\frac{S}{2.5} + 1\right)\left(\frac{S}{4.0} + 1\right)\left(\frac{S}{20} + 1\right)} \, .$$

where G_1 is the front panel-controlled gain, variable between 0.1 and 2.0. The lags at 4.0 and 20.0 radians per second shown in this transfer function are included for high frequency noise rejection. The combination of the lead at 0.6 radian and the lag at 2.5 radians serves to provide stable convergence to minimum pulse limit cycle operation.

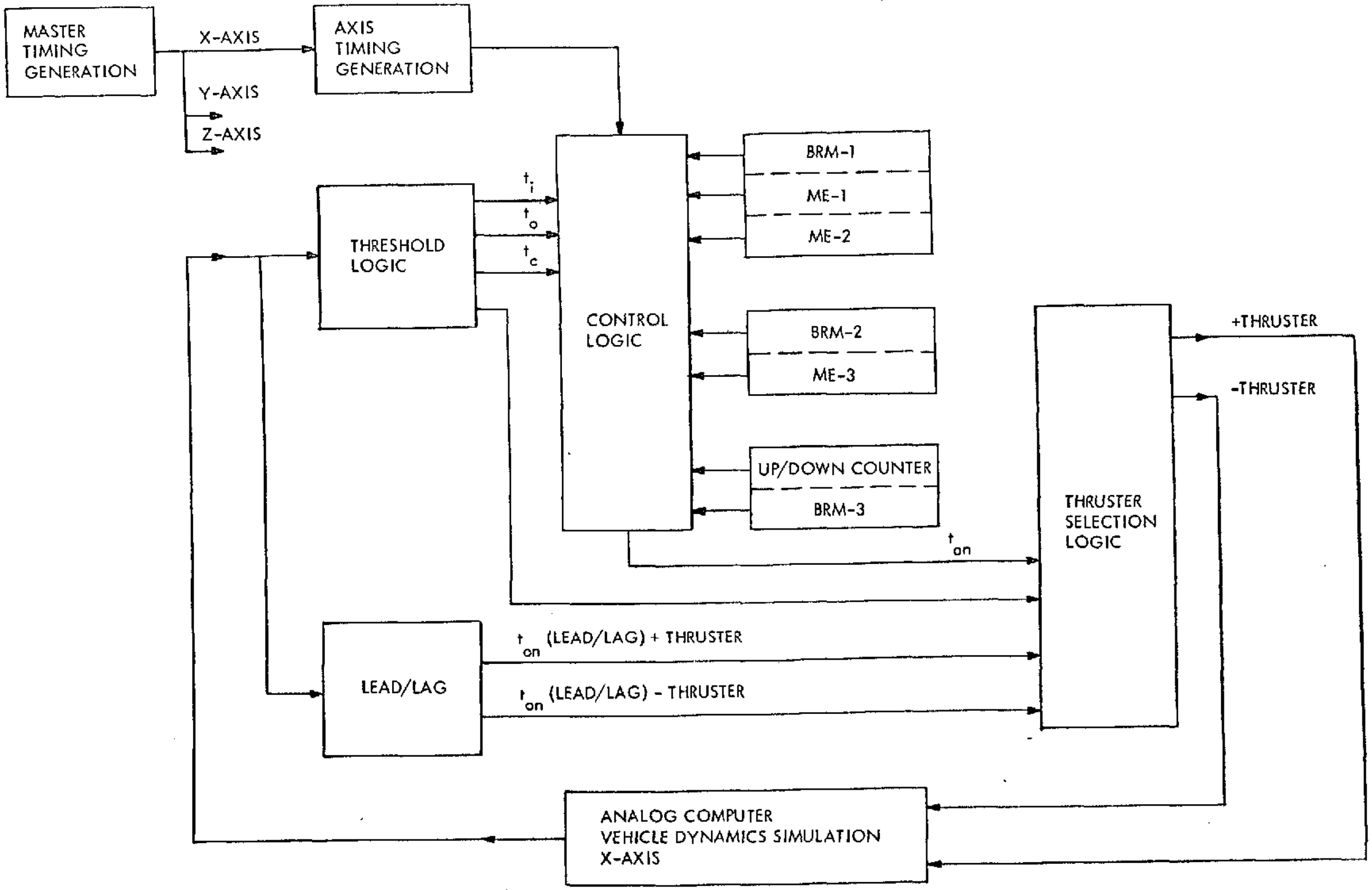


Figure 13. Functional Block Diagram of a Single Axis of the Adaptive Attitude Control Computer

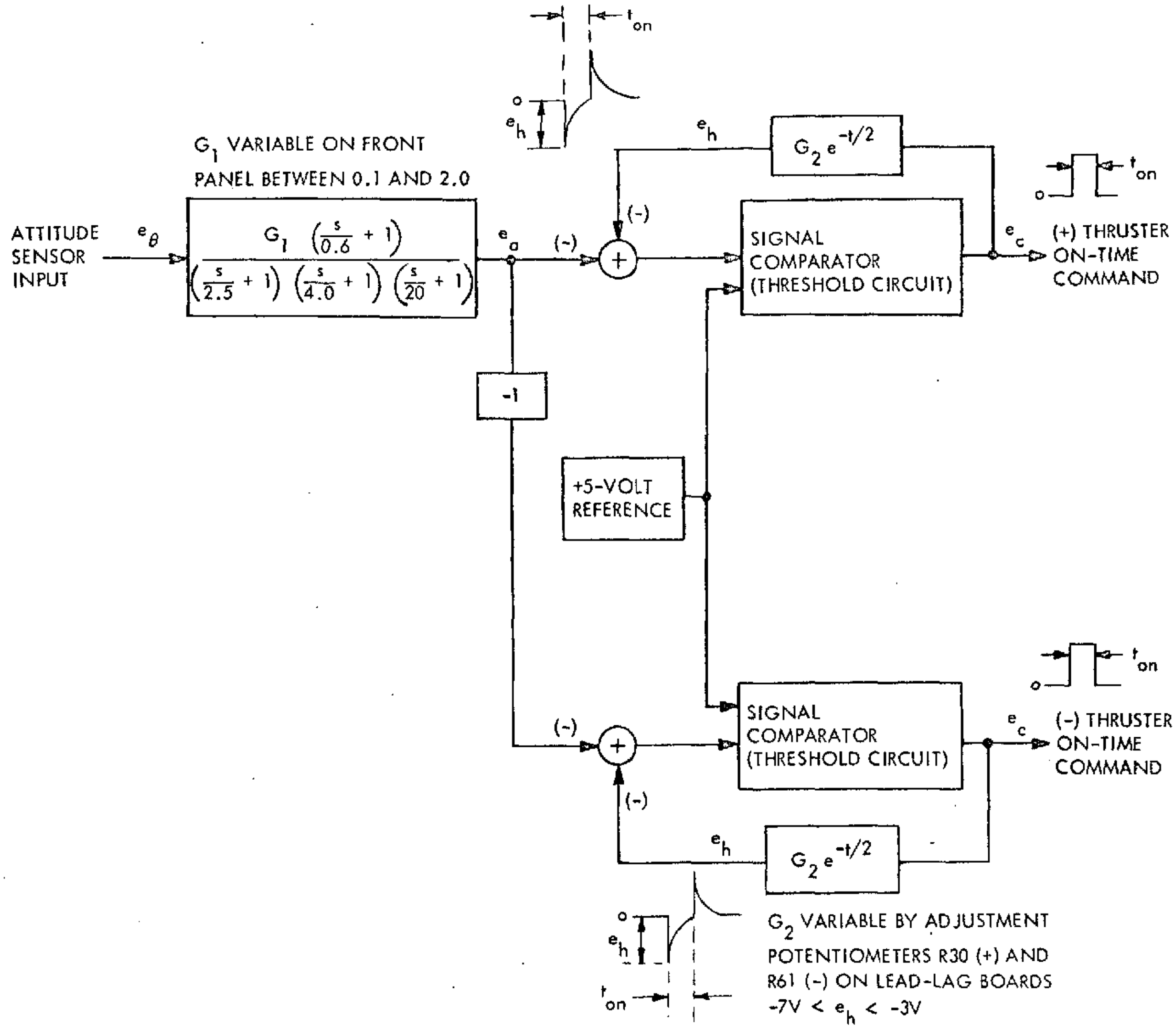


Figure 14. Functional Block Diagram of the Lead-Lag Electronic Subsystem

The signal e_a is fed directly to one of the signal comparators shown, and through a sign inverter to the other. When the signal at either comparator becomes equal to or greater than the 5-volt reference signal in magnitude (and opposite in sign) a thruster on-time command results. Neglecting for the moment the effects of the exponential hysteresis feedback signal (e_h), the thruster on-time command cuts off when $|e_a| < +5$ volts. In the absence of sensor noise (and still, for the moment, neglecting e_h) the minimum on-time command is a function of the selected ratio of control torque to vehicle moment of inertia, and the subsystem lags. However, due to the sensitivity of the lead-lag electronics to sensor input noise frequencies below 4 radians per second, excessive thruster command signal "chatter" will result in the presence of such input noise unless the exponential decay hysteresis signal (e_h) is employed.

The effect of the exponential hysteresis signal (e_h) is described as follows. At the instant that the signal comparator is triggered, a voltage which is the same polarity as e_a and whose instantaneous magnitude is equal to $G_2 e_c$ is summed with e_a. This summation effectively insures that any noise present in the signal e_a does not cause a "chatter" effect on the output of the comparator. (The magnitude $G_2 e_c$ can be adjusted by a potentiometer to be greater than the peak-to-peak magnitude of the noise.) The thruster will therefore remain on until the signal $(e_a + e_c G_2 e^{-t/2})$ has decayed to a point where it is equal to the 5-volt reference (and opposite in polarity) and the signal comparator reverts to its original state. At this point, e_h instantaneously changes by an amount equal to $-e_c G_2 e^{-t/2}$ volts thus effectively serving to inhibit the comparator from being triggered again due to noise. The thruster will therefore remain off since e_h decays toward zero with a time constant of two seconds. Such a scheme insures that thrust "chatter" does not occur, since depending upon the amount of sensor noise present, once the thruster is "on", a given amount of time must elapse (a function of noise and the 2-second time constant) before it can turn "off". Further, once it has turned off, it must remain off for an interval which is a function of noise, the 2-second time constant, and vehicle dynamics.

CONTROL LOGIC BRANCH

The optimizing and adaptive computation portion of the Adaptive Attitude Control Computer is the function of the Control Logic branch. This branch digitally solves the following equations for each of the three axis when time measurements derived from the vehicle position sensor for a given axis are obtained

$$t_{on} = \frac{I_V \theta_C}{T_c} \times \frac{t_i + 2t_o + K_1 \sqrt[4]{t_i t_o + t_o^2}}{t_i t_o + t_o^2} \quad \text{(parabolic)} \qquad (29)$$

$$t_{on} = \frac{1.5}{t_o} \times \frac{I_V \theta_c}{T_c} \quad \text{(standard)} \qquad (30)$$

$$t_{on} = t_{on} \pm (T_2 - T_1) \quad \text{(effective)} \qquad (31)$$

$$\frac{I_V \theta_c}{T} = \frac{t_{on}(t_i t_o + t_o^2)\, t_c}{t_c (2t_o + t_i + t_c) + (t_i t_o + t_o^2)} \quad \text{(gain)} \qquad (32)$$

These equations are divided into distinct mathematical sequential computations; addition, subtraction, multiplication, division and square root; which are used to compute the system "gain" (plant constant) and thruster "on" time A detailed explanation of the sequential mathematical computations begins on page 38.

Each of the three axes of the Control Logic branch requires four basic functions to sequentially solve the above equations. They are the:

1. threshold circuits
2. timing circuits
3. control logic circuits
4. computing element circuits

CONTROL LOGIC THRESHOLD

The threshold circuits establish the four vehicle electronic position thresholds and the hysteresis required for each axis, Figure 15.

The output from the vehicle position sensor is compared with predetermined voltage thresholds established by this circuit which have nominal values of θ_{db} = ± 5.0 vdc, $\theta_{db} - \theta_c = \pm 3.2$ vdc and Hysteresis = +0.25 vdc. The results of the comparison produces the times between threshold crossings and the sequence of threshold crossings to be used by the control logic circuits in the computation of the thruster on-time and the system gain.

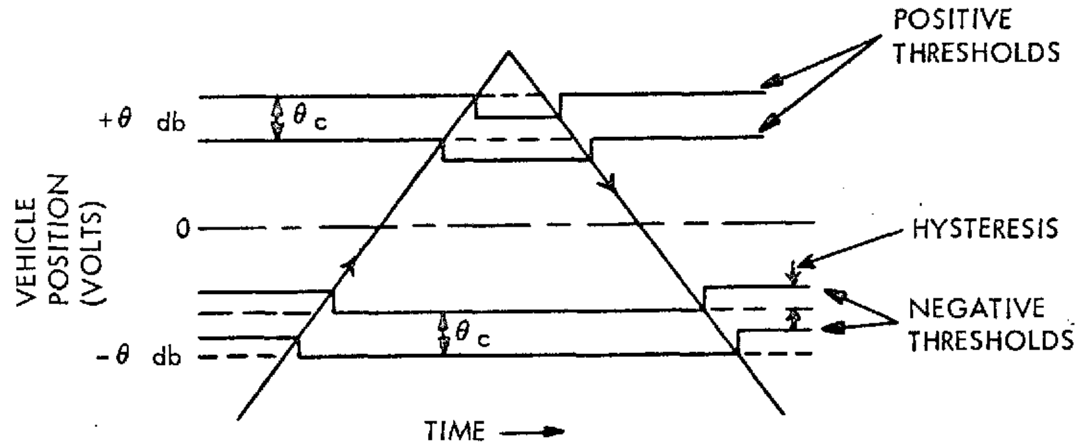


Figure 15. Control Logic Threshold and Computer Modes

TIMING CIRCUITS

The timing circuits generate the frequencies (pulse rates), pulse widths and synchronization required for the sequentially computed solution of equations 29, 30, 31, and 32 for each axis. The timing circuit boards are labeled T1, T2, T3 and T4 in the Adaptive Attitude Control Computer. The computer has three base units which are time, pulse rate and count. The first two are controlled by the timing circuits, the last by the number of counter stages in the computing elements.

The base pulse rate for each axis is 1024 KHz which is obtained from the output of a two-stage ripple counter driven by a 4096 KHz oscillator. All pulse rates used in the computer are derived from the 4096 KHz signal. These rates are used to convert the time between threshold crossings into a binary word (count), the multiplying constants, and the pulse rate used to convert the scaled value of the computed effective thruster on time to real time. These pulse rates vary from approximately 2048 KHz to below 1.0 Hz and are produced by a summation of out-of-phase pulse rates derived from a multistage synchronous counter.

CONTROL LOGIC CIRCUITS

Given (1) the threshold crossings, (2) the means to convert time intervals into a scaled value represented by a pulse rate or a pulse width, and (3) the generation of synchronization signals, control logic circuits are needed to "tell" the signals where and when to go. The control logic circuits establish one of the several computer modes, selects which thruster to fire (plus or minus control impulse), converts the threshold crossings into time-between-crossings, starts the computation cycle and gates the outputs of the computation elements (discussed later) to the proper computation element input.

Each axis has two basic modes to compute a thruster on time. These are labeled the "parabolic mode", equation 29, and the "standard mode", equation 30. Within each of these modes are two submodes labeled P and $\overline{P}$. When the computer is in the P mode it computes the thruster on time and when in the $\overline{P}$ mode it computes the system gain. The sequence of threshold crossings establishes the computer mode and time between thresholds. The computation of a thruster on time or gain establishes the P or $\overline{P}$ submodes.

The computer is automatically in the $\overline{P}$ submode immediately after the thruster on time has been computed and the thruster has fired. The P mode is established after the computer has made a system gain computation. The thruster on time computation is started immediately after the outer deadband threshold is exceeded. The system gain computation is made immediately after the inner-threshold ($\theta_{db} - \theta_c$) is crossed in a direction such that the magnitude of the position signal is decreasing if and only if the computer is in the parabolic mode. Figure 16 graphically illustrates the time measurements and the computer mode as a function of the sequence in which the thresholds are crossed.

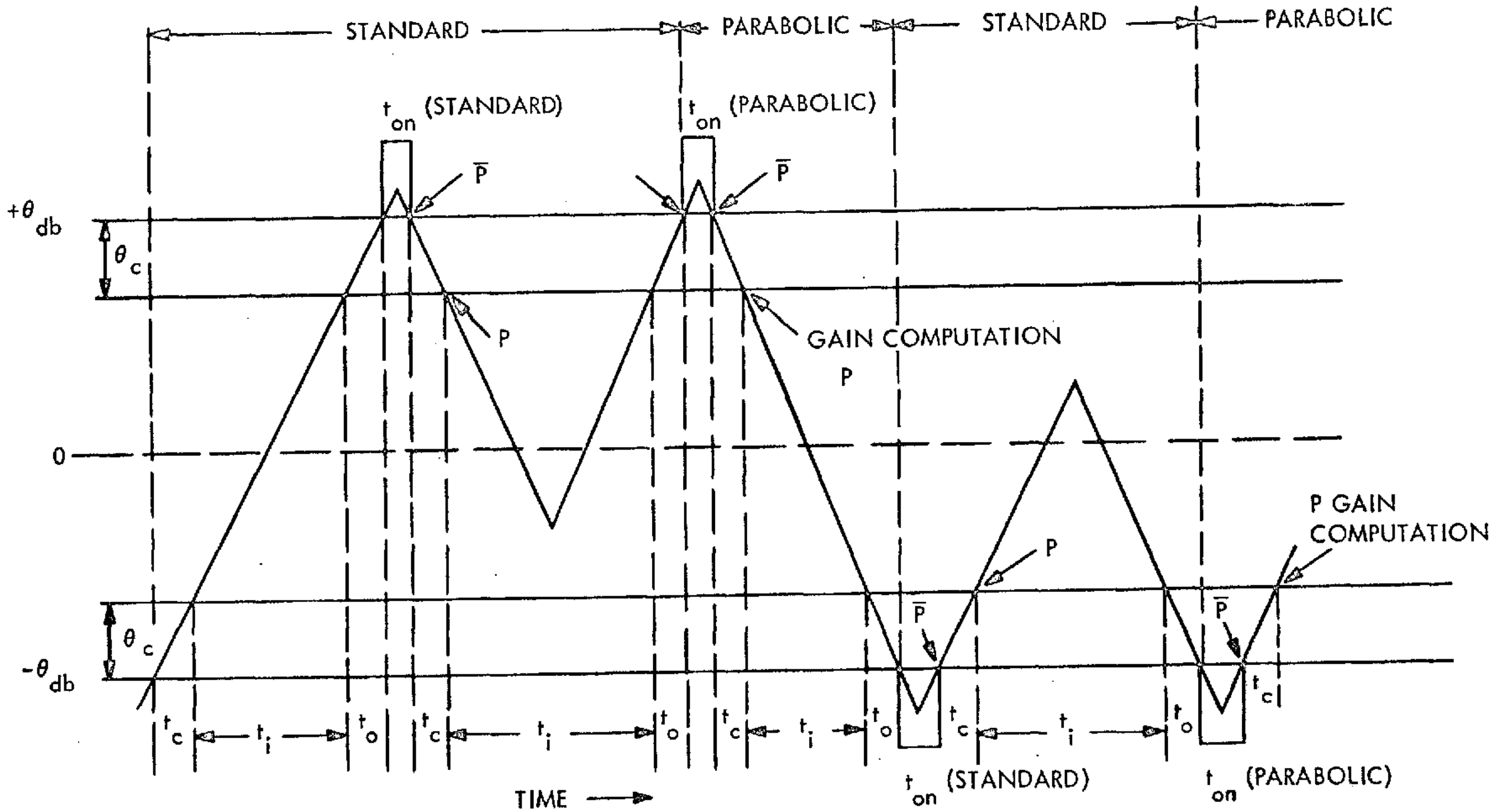


Figure 16. Control Logic Time Measurements and Computer Modes

COMPUTING ELEMENT CIRCUITS

The computing element circuits are synchronized by the timing and control logic circuits and receive inputs from the threshold and control logic circuits. The computing element circuits convert the values of time inputs into the scaled values of time represented by pulse widths and pulse rates so that the sequential solution of the "t_{on}" and "gain" equations may be obtained. Each axis of the Adaptive Attitude Control Computer has seven, 13-stage computing elements; three Memory Elements, three Binary Rate Multipliers (BRM) and one Up/Down (U/D) Counter. The following paragraphs explain the theory of operation of each of the different elements.

Memory Element

Since the computation is performed in a sequence of operations, an element is needed which will provide storage and periodic readout of certain problem variables to support the computation. The memory elements provide this by converting the variable, e.g., t_i, into a pulse width signal which occurs periodically, with a period of 8 msec, the base timing period. Referring to Figure 17.

$$t_o = t_s;\ \text{if } t_x = 0;\ t_s < T = 8 \text{ msec}$$

or

$$t_o = \frac{f_x}{f_c} t_x;\ \text{if } t_s = NT$$

$$(N-1)\ T < t_x < NT$$

$$N = 1, 2, 3, \ldots\ldots$$

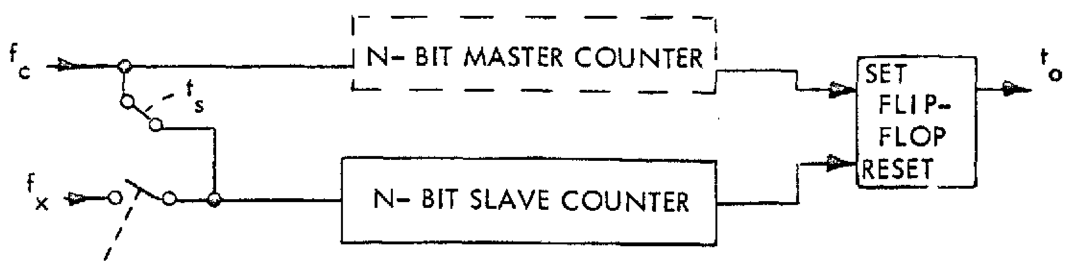


Figure 17. Block Diagram of Memory Element

The periodic pulse width signal output is generated by the phase difference between the memory element (slave) counter output and the master counter output. The master counter is driven continuously by the clock so that its output (or the state of the last stage flip-flop) is a constant frequency square wave which is used both to generate the base computation periods; and to supply the reference for the memory element counters.

If the slave counter is driven by the clock, and the two counters start together, then the two inputs to the output flip-flop occur simultaneously so that no output results. When the slave contains a count (e.g., a count representing t_x (Figure 17) and the two counters are driven by the clock, the counter outputs will be out of phase by an amount proportional to the count stored in the slave). The flip-flop converts this phase difference into a pulse width signal which occurs each period (T) of the master counter output.

There are two ways to introduce a variable into a memory element. The first is to interrupt the clock driving the slave counter during a portion (t_s) of one computation period so that in subsequent periods, the slave will lag behind by a time equal to that for which its clock was suspended. This is performed by supplying t_s which is a computer scaled pulse width signal representing some variable or constant while providing no t_x. Since the slave lags the clock, the memory element will occur at the beginning of each computation period. The second method is to suspend the clock drive to the slave for an integral number of computation periods and during the clock suspension, place a count into the slave using a frequency, f_x, other than the clock for a time, t_x. The clock must be suspended for an integral number of periods, NT, to avoid inadvertent memory element output by the first method above. With this method, the slave leads the master so that the memory output occurs at the end of each computation period.

Binary Rate Multiplier

The function of the Binary Rate Multiplier (BRM) is to convert from a count to a pulse rate. The BRM is shown schematically in Figure 18.

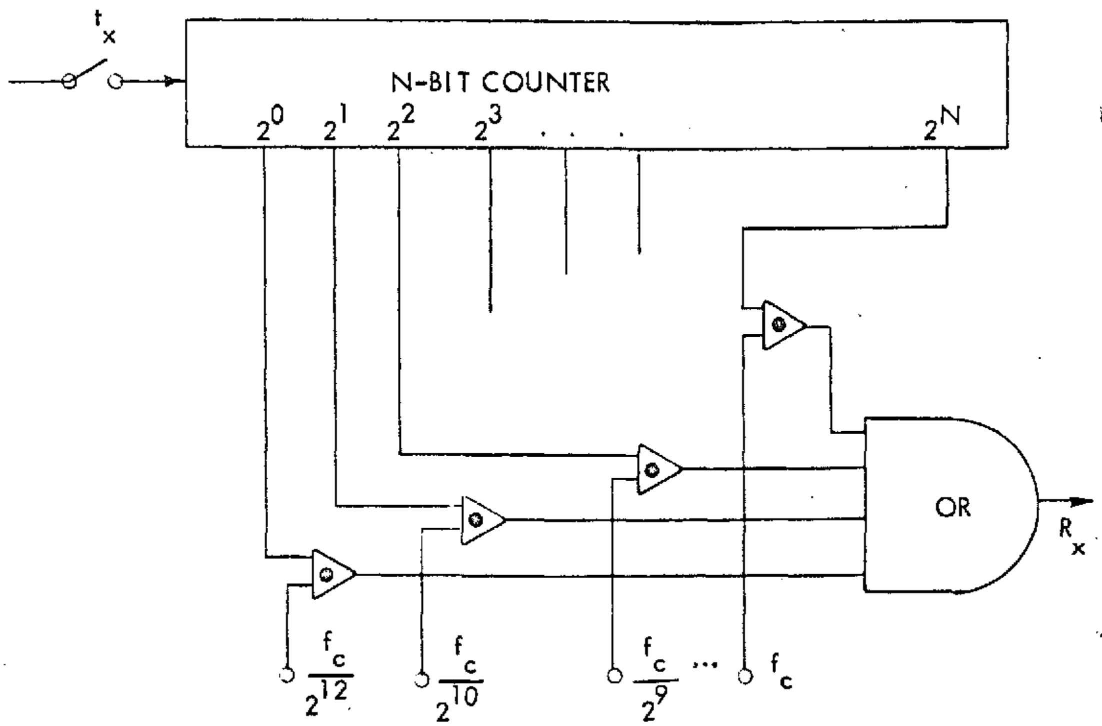


Figure 18. Block Diagram of a Binary Rate Multiplier

The input count, $t_x \cdot f_x$, is stored on a counter. The word, thus stored, is used to gate signals of various pulse rates into the output. The output is a pulse rate which is the sum of the various rates gated by the counter. The output increases $f_c/2^{12}$ Hertz for each input count to a maximum of $f_c + f_c/2 + f_c/4 + f_c/8 + \ldots + f_c/2^{12}$. The pulse rate signals used in the BRM are generated by the timing circuits.

$$R_x = \frac{2f_c}{\text{count in full counter}} \times \text{(count input to BRM during a computing period)}$$

Count input to BRM $= f_x t_x$, count in a fully counter $= 2^N$

The BRM is used for addition, multiplication, and conversion from pulse width to pulse rate.

Up/Down Counter

The U/D Counter perform addition, subtraction, division, multiplication, and square root operations. These operations are performed either by counting a pulse rate signal over an established time, or by measuring the time required to empty the counter at an established rate.

The U/D Counter is shown schematically in Figure 19. The output of an AND gate is zero only when the counter is empty. To demonstrate the division operation, assume that a frequency f_x is counted up for a time t_x so that

$$\text{Up Count} = \int_0^{t_x} f_x dt = f_x t_x$$

The counter is now counted down at a rate f_x so that

$$\text{Down Count} = f_y t_y$$

where t_y is the period to empty the counter. Since the Up Count and Down Count must be equal,

$$t_y = \frac{f_x t_x}{f_y} = \text{output pulse width}$$

The square root operation is performed by counting down using a frequency ramp where

$f_y = \frac{2f_c t_y}{T}$. If the up count is $t_x f_x$

then

$$t_x f_x = \int_0^{t_y} \frac{2 f_c t}{T} dt = \frac{f_c t_y^2}{T}$$

therefore

$$t_y = \left[\frac{T f_x t_x}{f_c}\right]^{1/2} = \text{output pulse width.}$$

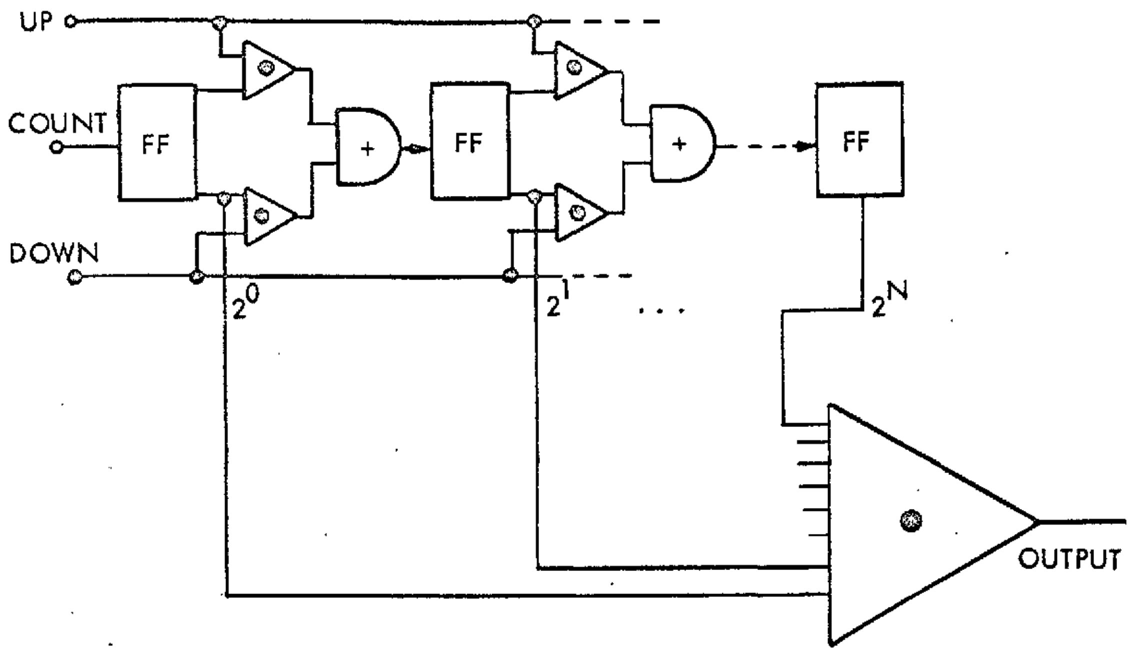


Figure 19. Block Diagram of an Up/Down Counter

ADAPTIVE ATTITUDE CONTROL COMPUTER TIME SEQUENTIAL OPERATION

The three-axis Adaptive Attitude Control Computer utilizes the same time sequential operation on each of the three axis. Figure 20 is the flow diagram of one axis. It is important to note that there are only seven computing logic elements for each axis. The flow diagram illustrates what computation is performed by each of seven elements at different times during the computation cycle. Each element may be used for a new purpose during each computation time period. The entire computational cycle is divided into "P" and "$\overline{P}$" modes in order to control the computations of t_{on} and Gain. The complete identification of a time period consists of P or $\overline{P}$, and times T_1, T_2, T_6 t_{on}, etc.

The following discussion is an explanation of the operation performed by each of the seven elements during each computation period with reference to the flow diagram of Figure 20.

A. Computation of t_{on} (Parabolic Mode)

$P \cdot t_i$

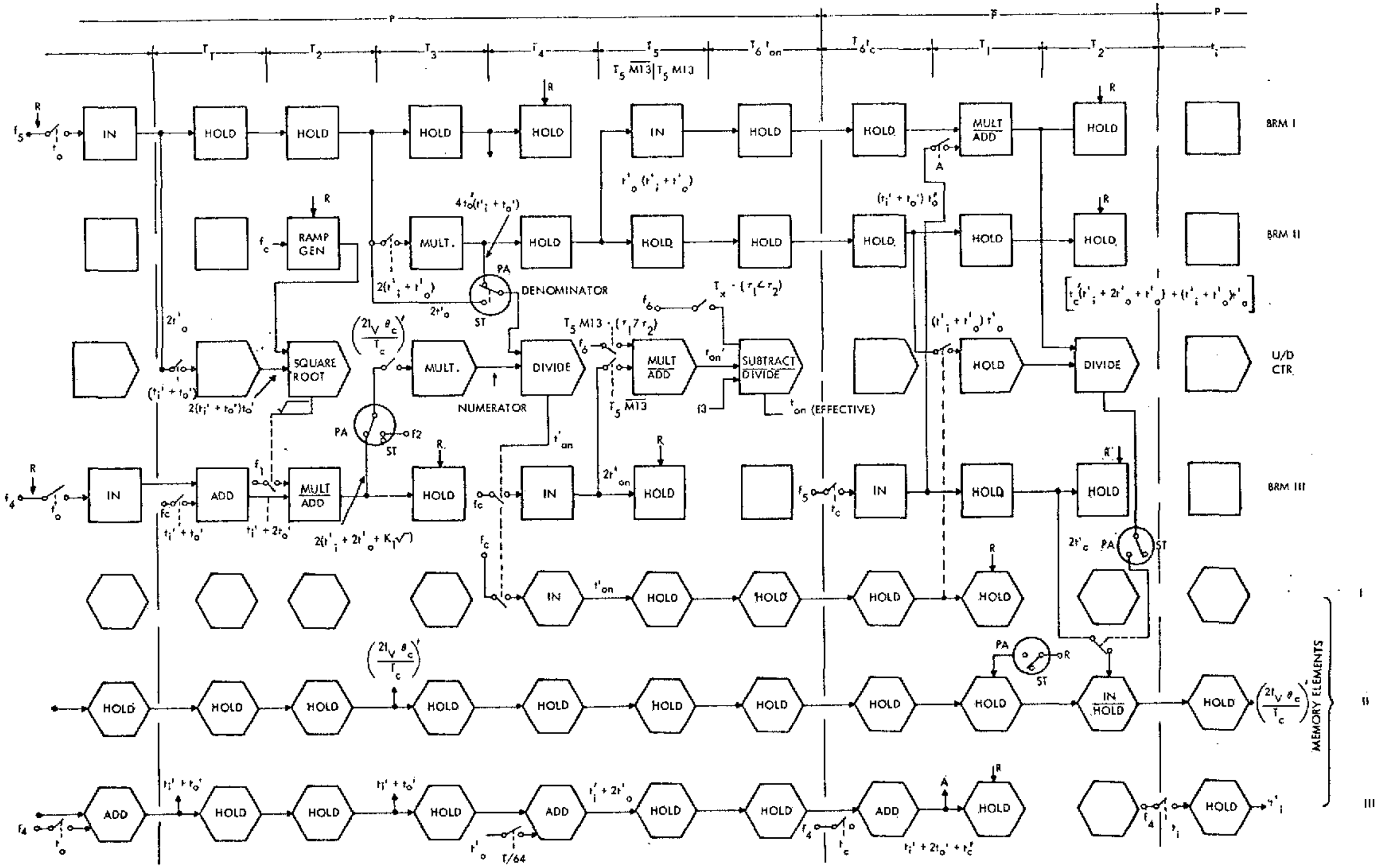
The real time signal, t_i, is input and scaled in ME3.

$P \cdot t_o$

The real time signal, t_o, is input, scaled and added to t_i in ME3. The same signal, t_o, is input and scaled in BRM I and BRM III. These elements are reset at the beginning of the t_o input.

$P \cdot T_1$

The time ($2 \times t_o'$), represented by a pulse rate is multiplied by ($t_i' + t_o'$) from ME3 and input into the U/D Counter. Also, ($t_i' + t_o'$) is added to t_o' in BRM III. At the end of T_1, the count in the U/D Counter is the scaled value of t_o (t_i + t_o); and the pulse rate out of BRM III is the scaled value of $t_i + 2t_o$.



PA = PARABOLIC MODE
ST = STANDARD MODE
R = RESET

PARABOLIC $t_{on} = \frac{I_v\theta_c}{T} \cdot \frac{t_i + 2t_o + K_1\sqrt{t_i t_o + t_o^2}}{t_i t_o + t_o^2}$ where $\frac{I_v\theta_c}{T} = \frac{t_{on(n-1)}(t_i t_o + t_o^2)\,t_c}{t_c(2t_o + t_i + t_c) + (t_i t_o + t_o^2)}$

WHERE $t_{on(n-1)}$ = LAST VALUE GENERATED

t_{on} (EFFECTIVE) = $t_{on} - (T_2 - T_1)$

OR

STANDARD $t_{on} = \frac{1.5}{t_o} \frac{I_v\theta_c}{T}$ where $\frac{I_v\theta_c}{T}$ = LAST VALUE GENERATED IN PREVIOUS MODE

Figure 20. Control Logic Time Sequential Operation-Flow Diagram

The scaled value of t_o from BRM I is rescaled and added to ME III and the BRM I is reset.

$P \cdot T_5$

The scaled value for t_{on} is transferred to the U/D Counter during the first half of $P \cdot T_5$. It is held in ME I for use in the gain computation during $\overline{P}$. If $(T_1 > T_2)$ the appropriate count is added to t'_{on} during the last half of $P \cdot T_5$.

The contents of BRM II, $2 \times t'_o (t'_i + t'_o)$, is stored in BRM I for use in the gain computation as $t'_o (t'_i + t'_o)$.

BRM III is reset.

$P \cdot T_6 \, t_{on}$

The scaled value of t_{on} is converted to real time by counting down the U/D Counter with a constant pulse rate f_3. The constant $(T_2 - T_1)$ is subtracted from t'_{on} to produce the output of t_{on} (effective) if T_1 is less than T_2.

B. Computation of Gain $\dfrac{2 \, I_V \, \theta_C}{T_c}$

$\overline{P} \cdot T_6 \, t_c$

The real time, t_c, is scaled at the input operation to BRM III and added to $(t'_i + 2t'_o)$ in ME III to produce the pulse width representing $(t' + 2t'_o + t'_c)$.

$\overline{P} \cdot T_1$

$P \cdot T_2$

The output of BRM II is a ramp of pulse rate which reaches a maximum value of $2f_c$, or twice the clock frequency. The ramp is used to count down the U/D Counter in which $t_o'(t_i' + t_o')$ is stored. The time required to count down is a pulse width representing the square root of t_o' times $(t_i' + t_o')$. This pulse width is multiplied by the constant pulse rate f_1 to produce the scaled value of $K_1 \sqrt{t_o (t_i + t_o)}$. This count is added to the existing count in BRM III.

BRM II is reset at the end of $P \cdot T_2$.

$P \cdot T_3$

Four times the numerator of the expression for t_{on} is stored in the U/D Counter by multiplying the pulse rate from BRM III that represents $2\left(t_i' + 2t_o' + K_1\sqrt{(t_i' + t_o')t_o'}\right)$ and the pulse width representing $\left(\frac{2 I_V \theta_c}{T_c}\right)'$. The quantity $(2 I_V \theta_c / T_c)'$ was stored in ME II during the previous computation cycle or preset into ME II at the beginning of the problem.

The product of $2 \times t_o'$ from BRM I and $(t_i' + t_o')$ from ME3 is taken by BRM II to form twice the denominator of the expression for t_{on}.

BRM III is reset at the end of this period.

$P \cdot T_4$

The pulse rate representing $4t_o'(t_i' + t_o')$ from BRM II is used to count down the U/D Counter. The resulting pulse width represents t_{on}' and is stored in BRM III and ME1.

The pulse width of $(t_i' + 2t_o' + t_c')$ from ME III is multiplied by the pulse rate of t_c' from BRM III and the result is added to the stored value of $(t_i' + t_o')\, t_o'$ producing $\left[t_c'\,(2t_o' + t_i' + t_c') + (t_i' + t_o')\, t_o'\right]$ in BRM I. This is the denominator of the gain equation.

The pulse rate representing $t_o'\,(t_i' + t_o')$ from BRM II is multiplied by the pulse width of (t_{on}') stored in MEI to produce the numerator of the gain equation (divided by t_c) in the Up/Down Counter.

ME II is reset unless the computation of a standard pulse is required. ME III is reset.

$\overline{P} \cdot T_2$

Pulse rate analog from BRM I is used to count down the Up/Down Counter. This produces the pulse width representing $\left(\frac{I_V\, \theta_c}{T_c\, t_c}\right)'$.

The pulse rate of $2\, t_c'$ is multiplied by this pulse width producing $\left(\frac{2\, I_V\, \theta_c}{T_c}\right)'$. The scaled gain is stored in ME II for the next calculation of t_{on}.

BRM I, BRM II, and BRM III are reset.

$\overline{P}\, T_3$ through $\overline{P}\, T_6$

These timing periods are not used in the gain computation sequence.

C. Computation of t_{on} (Standard Mode)

Only the time input representing t_o is required for this computation sequence. The same events occur that were explained for the t_{on} parabolic computation with the exceptions noted below.

$\underline{P \cdot T_3}$

The constant 1.5 represented by the pulse rate of f_2 is multiplied by the pulse width representing the system gain. The result is stored in the U/D Counter.

$\underline{P \cdot T_4}$

The pulse rate representing $2\,t_0'$ from BRM I is used to count down the U/D Counter. The resulting pulse width represents the scaled value of t_{on}.

CIRCUIT CARD DESCRIPTION

In the Adaptive Attitude Control Computer one axis of computation requires four timing boards, a logic threshold board, five boards containing the sequential analog to digital computing elements (3-memory elements, 3-binary rate multipliers, one up/down counter plus associated control logic), and one lead-lag circuit board.

The four timing boards are multi-purpose in that they generate the timing signals common to all three axes. Each of the seven other boards mentioned above are identically used in each computational axis. The following is a summary description of each circuit board.

TIMING BOARD T1

Schematic 854D311
Assembly 854D301

This board takes as its input the 4.096 MHz, 50 percent duty cycle square wave from the crystal oscillator (Specification Control Drawing 931C100) and produces a basic 1.024 MHz clock signal and all other frequencies (pulse rates) required by the computer. To obtain these frequencies, a counter consisting of 23 flip-flops and appropriate gating is used. All frequencies consist of pulses of 125-nanosecond width.

Two other signals generated by this board are T/64, a pulse width used for gating during a computing cycle, and T_r the reset pulse with period 8 m sec and pulse width 1 μ sec. This is used to reset various computing elements during a computing cycle.

TIMING BOARD T2

Schematic	854D312
Assembly	854D302

This board takes the frequencies generated on board T1 and combines them using "OR" gates to generate the scaling frequencies f_3 and f_6. These values are determined by the front panel switches. Also generated on this board are the 4 m sec pulse width signals T_{X-x}, T_{X-y}, and T_{X-z} used for the purpose of subtracting a constant from the computed t_{on} when the thruster rise time constant is less than the thruster fall time constant, $\tau_1 < \tau_2$.

TIMING BOARD T3

Schematic	843D313
Assembly	854D303

Timing board T3 generates the scaling frequency $f_4 = f_5/64$ for each axis and also has on it the three ring counters used to generate the computing periods T1 through T6 for each axis. Each computing period T1 through T6, see Figure 20, is 8 m sec. Computing cycles are initiated at the end of each "t_o" measurement and at the end of each "t_c" measurement.

TIMING BOARD T4

Schematic	854D314
Assembly	854D304

This board takes the frequencies generated on board T1 and combines them using "OR" gates to generate the scaling frequency f_5 for each axis. The value of f_5 is determined by front panel switches.

LOGIC THRESHOLD BOARD

Schematic	854D320
Assembly	177F243

The logic threshold board takes as its input an analog voltage representing vehicle attitude θ and by use of four Fairchild μA710 comparators generates the logic signals A, B, C and D. These signals together with the "logic threshold" gain control potentiometer on the front panel define the deadband attitude limits $\pm \theta_{db}$ and the $\theta_{db} - \theta_c$ deadband.

The logic signals A, B, C and D are used to generate pulse widths representing the t_i, t_o, and t_c measurements to be used by the Adaptive Attitude Control Computer. Figure 21 shows the definition of the logic signals A, B, C, and D.

Adjustment potentiometers are provided on this board for adjustment of the threshold and hysteresis of each μA710 comparator. The threshold adjustment procedure is discussed in the "Operating Instructions" Section. The thresholds are nominally set at +5 vdc, +3.2 vdc, - 3.2 vdc and -5 vdc as measured at TP16 on the board. The hysteresis for each is set at 0.25 vdc. Noise rejection circuits (single-lag) are also included on this board with nominal time constants of 0.05 cycles/second.

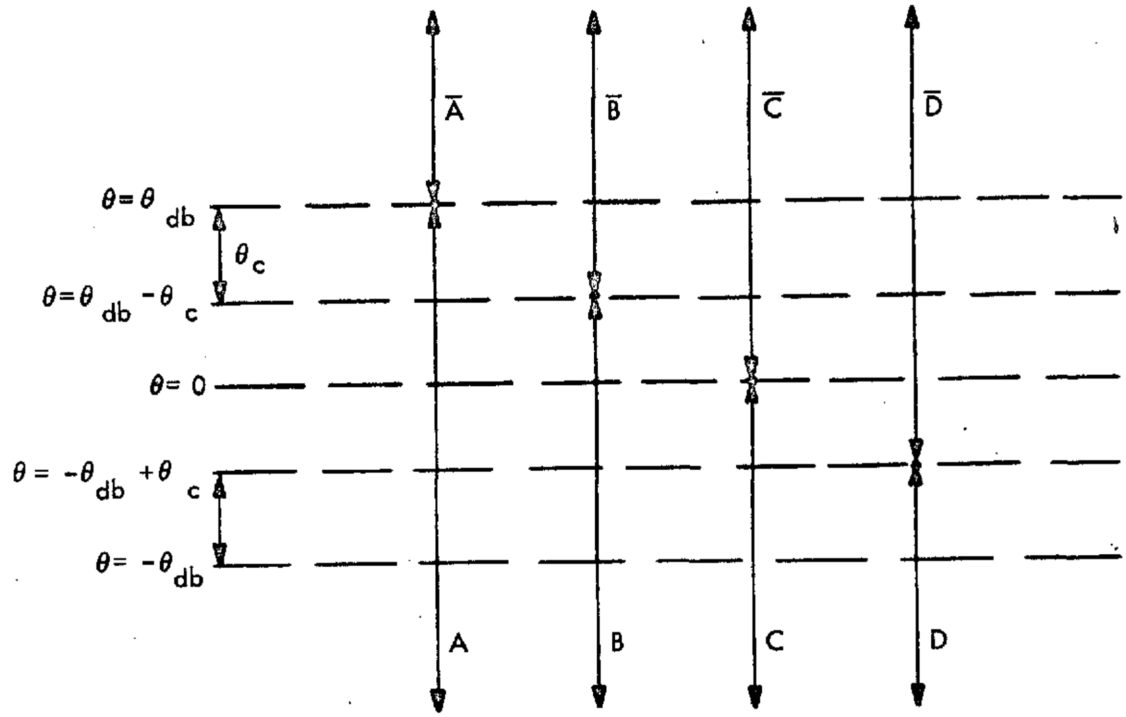


Figure 21. Definition of Logic Signals A, B, C and D

COMPUTATION BOARD

Schematic	854D315
Assembly	854D305

One of these boards is required for each axis. Scaling frequency f_1 (controlled by front panel switching) is generated on this board by gating frequencies from the timing boards. Binary Rate Multiplier #1 (BRM 1), part of the control logic defined by the flow diagram in Figure 20, and the front panel gain insertion logic are included on this board. The time measurement t_c and the (+) and (-) thruster selection logic signals are also generated on this board.

COMPUTATION BOARD

Schematic	843D316
Assembly	854D306

One of these boards is required for each axis. On this board are BRM 2, Memory Element #3 (ME3) and another part of the control logic defined by the flow diagram. Also generated on this board are the pulse width signals t_i and t_o and the standard (ST) and parabolic ($\overline{ST}$) control signals.

COMPUTATION BOARD

Schematic	854D317
Assembly	854D307

There are three of these boards in the computer, one for each axis. On this board the remainder of the control logic signals defined by the flow diagram are generated.

COMPUTATION BOARD

Schematic	854D318
Assembly	854D308

This board contains the computing elements BRM3 and ME1. Three of these boards are used in the system.

COMPUTATION BOARD

Schematic	854D319
Assembly	854D309

This board contains ME2 in which the gain constant is stored as a pulse width and the up/down counter. The up/down counter is used during each computing cycle and its output during P • T6 defines the computed thruster "on" time. One of these boards is required for each axis.

LEAD-LAG BOARD

Schematic	854D321
Assembly	177F242

The lead-lag boards provide control to the vehicle when the attitude and angular rate are large, as during the Maneuver and Acquisition. The analog signal representing vehicle attitude is applied to the lead-lag board through the Maneuver and Acquisition gain control potentiometer on the front panel. Amplifier A1 provides gain and a lag filter for noise rejection. The lead-lag transfer function is formed by amplifiers A2 and A3. Amplifiers A4 and A6 are buffers which trigger negative and positive threshold circuits for turning on the thruster. The outputs of the two μ A710 comparators are gated with the computed t_{on} for controlling the final t_{on+} and t_{on-} signals. The collectors of Q3 and Q6 give the required output voltage and current for the thruster "on" signals.

The lead-lag transfer function excluding the gain level, but including two lag breaks for noise rejection is given by:

$$\frac{E_o(S)}{E_{in}(S)} = \frac{(\frac{1}{0.6} S + 1)}{(\frac{1}{2.5} S + 1)(\frac{1}{4.0} S + 1)(\frac{1}{20} S + 1)}$$

$$= \frac{(T_A S + 1)}{(T_B S + 1)\left[S \frac{C_1 C_2}{C_1 C_2} \quad \frac{R_4 R_5}{R_4 R_5} + 1\right](T_c S + 1)}$$

$$\tau_A = \frac{1}{0.6} = 1.67$$

$$\tau_B = \frac{1}{2.5} = 0.4$$

$$\tau_C = \frac{1}{20} = 0.05$$

$$\frac{E_o(S)}{E_{in}(S)} = \frac{(\tau_A S + 1)}{\left[\tau_B \quad \tau_C S^2 + (\tau_B + \tau_C) S + 1\right]\left[S \quad \frac{C_1 C_2}{C_1 + C_2} \quad \frac{R_4 R_5}{R_4 + R_5} + 1\right]}$$

$$\tau_B \quad \tau_C = \frac{\tau_1 \quad \tau_2}{1 + K_2 K_3 K_4} \qquad \text{and}$$

$$\tau_B \quad \tau_C = \frac{\tau_1 + \tau_2 + K_2 K_3 K_4 \quad \tau_3}{1 + K_2 K_3 K_4}$$

Where:

$$K_1 = \frac{R9}{R7}$$

$$K_2 = \frac{R48}{R48 + R49}$$

$$K_3 = \frac{R46}{R47}$$

$$K_4 = \frac{R7 + R9}{R7}$$

$$\tau_1 = \left(\frac{R43\ R46}{R47} + R43 + R46\right) C24$$

$$\tau_2 = R9\ (C5)$$

$$\tau_3 = \left(\frac{R7\ R9}{R7 + R9}\right) C5$$

SECTION IV

OPERATING INSTRUCTIONS

COMPUTER SCALING

The Adaptive Attitude Control Computer can be scaled for a wide range of combinations of vehicle inertia, I_V, attitude deadbands, θ_{db}, control torques, T_c, and thruster rise and fall time constants τ_1 and τ_2. The range of each variable is

100	$\leq$	I_V	$\leq$	5000	slug-ft^2
0.1	$\leq$	$\lvert\theta_{db}\rvert$	$\leq$	1.0	degree
0	$\leq$	τ_1	$\leq$	3.0	seconds
0	$\leq$	τ_2	$\leq$	3.0	seconds
0.2	$\geq$	T_c	$\geq$	0.005	ft-lb

The computer will optimally control the vehicle attitude in a bias torque environment over a dynamic range of at least 2.0×10^{-4} to 5.85×10^{-6} ft-lb for any combination of I_V, θ_{db}, τ_1, τ_2 and T_c.

The Adaptive Attitude Control Computer has two parallel control branches that must be scaled for a given set of variables. One branch is an analog lead-lag circuit with fixed slopes (-60°) to the switching lines. The crossover on the position axis of a phase plane plot can be varied from 0.1° to 2.0° by adjusting the axis gain potentiometer located on the front panel of the computer. Refer to Figure 22.

The control logic branch has four variables to be adjusted for any given set of I_V, θ_{db}, τ_1, τ_2 and T_c. The position threshold is easily set from 0.1 to 1.0 degree by adjusting the control logic threshold gain potentiometer for any axis. These potentiometers are located next to the Maneuver and Acquisition potentiometers on the front panel. The other three adjustments are of primary interest since the philosophy

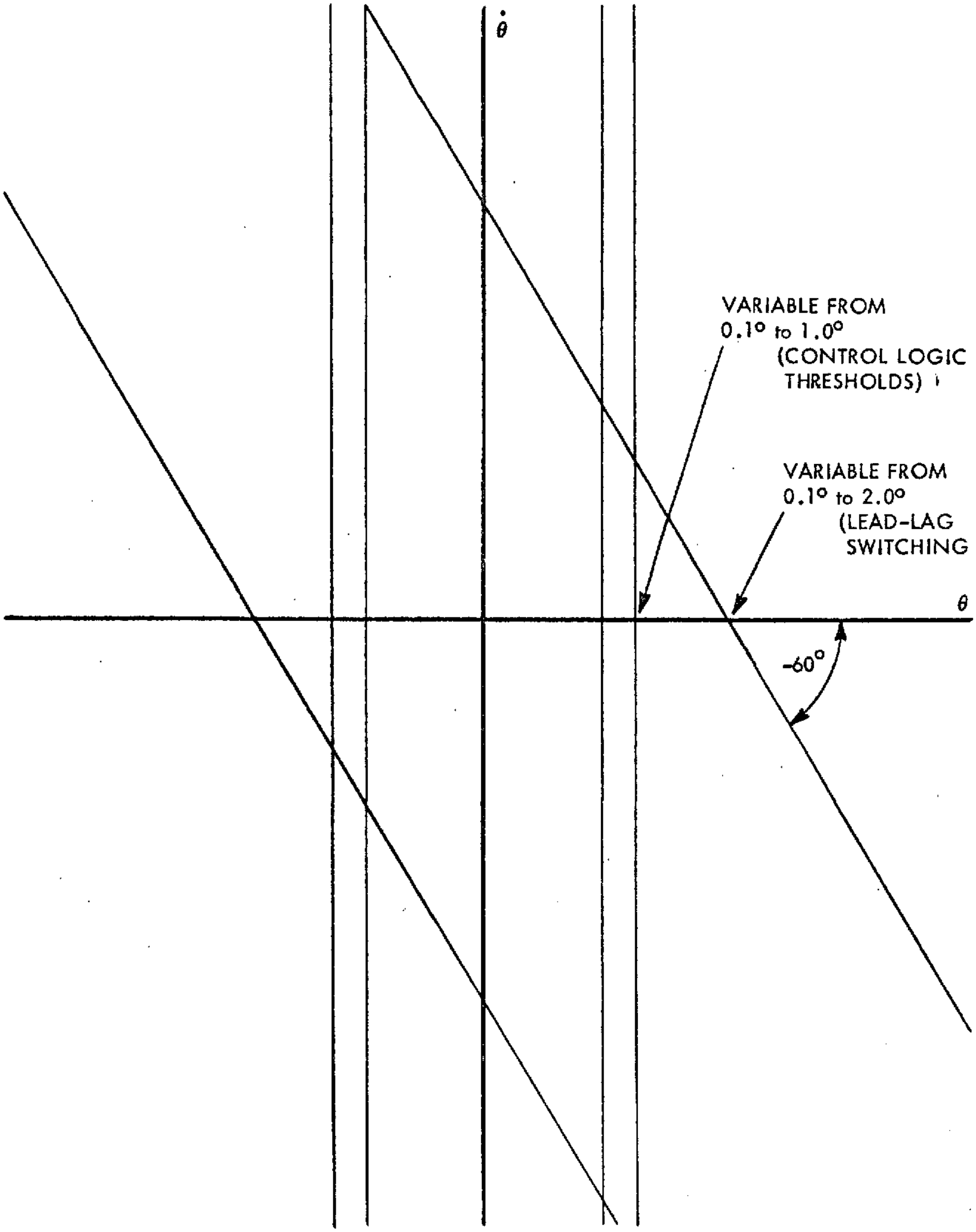


Figure 22. Phase Plane Illustration of Threshold Controls

used affects the dynamic range of bias torque over which the computer can control in an optimum fashion and the accuracy of the computations under the extreme conditions.

The three adjustments for scaling, to be discussed, all deal with the value of the pulse rate used to convert from real time to scaled values of time-between-threshold crossings, t_i, t_o, t_c and the conversion from a scaled value of thruster on time to real time.

The base units for scaling the Adaptive Attitude Control Computer are count; as determined by the number of stages in the Memory Element, BRM, and U/D Counter; the clock frequency and the computer time base. The value of these base units are

Count	=	8192
Frequency (pulse rate)	=	1024 kHz
Time	=	8 msec

so that

$$\frac{\text{Count}}{\text{Pulse Rate}} = \text{Time}$$

or

$$\frac{8192}{1024 \times 10^3} = 8 \times 10^{-3} \text{ second}$$

The input time variables (t_x) are scaled so that

$$t_x \text{ (max)} = 8192 \text{ count}$$

or

$$t_x \text{ (max)} = 1024 \text{ kHz}$$

or

$$t_x \text{ (max)} = 8 \times 10^{-3} \text{ second}$$

Each of the input times; t_i, t_o, t_c; are converted to a count, binary word, during the input operation. This is accomplished by gating, with logic circuits, the time-between-threshold crossings and a pulse rate

$$f_x \times t_x = \text{count}$$

Therefore, if the maximum time-between-threshold crossings is known, the pulse rate required for a maximum count to represent maximum time can be obtained.

$$f_x = \frac{\text{max count}}{t_x \text{ (max)}}$$

The Adaptive Attitude Control Computer is automatically scaled for the time measurement t_i once the scaling for the t_o time measurement is selected. The choice of the input pulse rate for the t_o time measurement affects the resolution and accuracy of the computation. The primary concern is to have enough resolution (i.e., count in the BRM I counter) when the vehicle is operating in the maximum bias torque environment, small values of t_o.

The philosophy used to choose the scaling frequency, f_5, for t_o is to determine what count should be in the counter under conditions of maximum bias torque so that the resolution is adequate enough for accurate computations. The required count was empirically determined to be 1400 counts. Therefore

$$f_5 = \frac{1400}{t_o \text{ (min)}} \tag{33}$$

where t_o (min) is the time it takes the vehicle to cross the thresholds separated by the angle θ_c when the vehicle is in a parabolic limit cycle with a $2\ \theta_{db}$ depth and $T_b = 2.0 \times 10^{-4}$ ft-lb. The equation for this expression is derived below:

$$\theta (t) = \frac{T_b \text{ (max)}}{2\ I_V}\ t^2 + \dot{\theta}_o t + \theta_o \tag{34}$$

Solving for the time (t_d) to reach zero rate at a depth of $2\,\theta_{db}$

$$-\theta_{db} = \frac{T_b\,(\max)}{2\,I_V}\,t_d^2 - \frac{T_b\,(\max)}{I_V}\,t_d^2 + \theta_{db}$$

$$t_d = \left[\frac{4\,\theta_{db}\,I_V}{T_b\,(\max)}\right]^{1/2}$$

Solving for the time (t_o) to cross from the outer to the inner threshold

$$\theta_{db} - \theta_c = \frac{T_b\,(\max)}{2\,I_V}\,t_o^2 - \frac{T_b\,(\max)}{I_V}\,t_d t_o + \theta_{db}$$

$$t_o = t_d \pm \left[t_d^2 - \frac{2\,\theta_c\,I_V}{T_b\,(\max)}\right]^{1/2}$$

Therefore by substitution

$$t_o\,(\min) = \left\{2 - \left[4 - \frac{2\,\theta_c}{\theta_{db}}\right]^{1/2}\right\}\left|\left[\frac{\theta_{db}\,I_V}{T_b\,(\max)}\right]^{1/2}\right| \tag{35}$$

Since the maximum count, 8192, will represent the maximum t_o, the dynamic range of bias torque can be determined

$$\frac{t_o\,(\max)}{t_o\,(\min)} = \left[\frac{T_b\,(\max)}{T_b\,(\min)}\right]^{1/2} = \frac{8192}{1400}$$

Therefore

$$T_b\,(\min) = 5.85 \times 10^{-6}\ \text{ft-lb}$$

for $\quad T_b\,(\max) = 2.0 \times 10^{-4}$ ft-lb

and $\quad t_o\,(\max) = 5.85\ t_o\,(\min)$

Examination of equations 33 and 35 shows that the scaling for the time variable, t_o, is a function of a constant, determined empirically (1400 count), and a function of the computer threshold (θ_c/θ_{db}). An increase in the 144 count will improve the accuracy of the computation under the maximum bias torque environment. The trade-off for this increase is a reduction in the dynamic range of optimum control, i.e., the present value of T_b (min) increases. This trade-off could be desirably given a particular mission. The ratio θ_c/θ_{db} has been preset into the threshold circuit but it can be adjusted. If θ_c is changed, a new value of t_o (min) must be calculated. The trade-off for changing θ_c is not a function of scaling but a function of the signal to noise ratio; i.e., an increase in the signal to noise ratio may allow a decrease in (θ_c/θ_{db}).

The next factor considered in the scaling philosophy is that of optimum operation in a minimum bias torque environment. In the previous discussion it was pointed out that the counters had maximum count corresponding to maximum time variables. The maximum time-between-threshold crossings for optimum control occurs when bias torque is at a minimum. When the counters are full, the control logic branch of the computer computes its minimum thruster firing time. It is now important to choose the desired minimum firing time so that it corresponds to the minimum bias torque conditions. This is accomplished by choosing a proper level of control torque based upon the vehicle inertia, attitude thresholds, and desired minimum thruster firing time. The thruster firing time equation for minimum impulse is determined by:

$$t_{on}\ (\text{min}) = \frac{1.5\ I_V \theta_c}{t_c t_o\ (\text{max})}$$

Knowing t_{on} (min), θ_c, t_o (max), I_V one can calculate the correct value of T_c

$$\frac{1.5\ I_V\ \theta_c}{t_{on}\ (\text{min})\ t_o\ (\text{max})} \tag{36}$$

The choice of t_{on} (min) must take into account the rise (τ_1) and fall (τ_2) time constants. From a specific impulse efficiency viewpoint, it is desirable to have the minimum thruster on time equal to at least three rise time constants

$$t_{on}\,(\text{min}) = 3\,\tau_1$$

If $\tau_1 = \tau_2$, the actual impulse (area under the curve) can be represented at a square pulse. The control logic branch makes the t_{on} computation based on a square pulse. Therefore for $\tau_1 = \tau_2$

$$t_{on}\,(\text{effective}) = t_{on}\,(\text{calculated})$$

$$\text{or} \quad t_{on}\,(\text{min})\text{ effective} = t_{on}\,(\text{min})$$

When τ_1 does not equal τ_2, the square pulse representation of the actual on time can be shown to equal that of square pulse plus or minus the magnitude of ($\tau_1 - \tau_2$)

$$t_{on}\,(\text{effective}) = t_{on}\,(\text{calculated}) \pm \left|\tau_1 - \tau_2\right|$$

For $\tau_1 > \tau_2$

$$t_{on}\,(\text{effective}) = t_{on}\,(\text{calculated}) - \left|\tau_1 - \tau_2\right|$$

Therefore

$$t_{on}\,(\text{min}) = 3\,\tau_1 - \left|\tau_1 - \tau_2\right|$$

For $\tau_1 < \tau_2$

$$t_{on}\,(\text{effective}) = t_{on}\,(\text{calculated}) + \left|\tau_1 - \tau_2\right|$$

Therefore

$$t_{on}\,(\text{min}) = 3\,\tau_1 + \left|\tau_1 - \tau_2\right|$$

To determine the pulse rate required to convert the scaled value of t_{on} to real time the value of t_{on}, maximum, must be determined.

$$f_3 = \frac{8192}{t_{on}\,(max)} \qquad (37)$$

The actual ratio of thruster on time for the parabolic limit cycle is

$$\frac{t_{on}\,(max)}{t_{on}\,(min)} = \left[\frac{T_b\,(max)}{T_b\,(min)}\right]^{1/2} = 5.85$$

To allow at least a 75 percent safety factor on maximum on time, since the required thruster on time will be higher during the acquisition of the optimum limit cycle, and the minimum on time in the standard mode is less than the minimum on time in the parabolic mode, let

$$t_{on}(max) = 10\, t_{on}\,(min)$$

Knowing the scaling of thruster firing time, the scaled value of $\left| \tau_1 - \tau_2 \right|$ can be determined. The magnitude of $(\tau_1 - \tau_2)$ must be added or subtracted from the calculated value of the square pulse firing time. This operation is accomplished in the computer while the firing time is in a scaled value represented by count in a BRM. Therefore, the appropriate amount of scaled count must be added or subtracted.

In the computer this count is added or subtracted during a fixed time period equal to 4×10^{-3} second. Therefore, the pulse rate, f_6, used to add or subtract the count can be determined since

$$\frac{\text{Count added or subtracted}}{f_3} = \left| \tau_1 - \tau_2 \right|$$

or $$\frac{f_6\,(4 \times 10^{-3})}{f_3} = \left| \tau_1 - \tau_2 \right|$$

or $$f_6 = \frac{f_3 \left| \tau_1 - \tau_2 \right|}{4 \times 10^{-3}} \qquad (38)$$

The equations 33, 37 and 38 must now be expressed in values that transfer them to the front panel parameters of the Adaptive Attitude Control Computer. The panel has a series of numbers beginning with 1 and increasing to 1024 by powers of two, i.e., 2^N where N = 0, 1, 2, 3 . . . 10. Below the numbers are a series of switches labeled F1, F3, F5 and F6. The F1 switches are for scallop depth (target) selection which is discussed in the Operating Mechanics Section. The switches labeled F3, F5 and F6 correspond to values of f_3, f_5 and f_6. When the switch is in the up position it allows a pulse rate to be summed. The total sum of the individual pulse rates must equal to f_3, f_5 and f_6. Knowing what pulse rate is summed when the switch labeled 1024 is up will allow the determination of the constant that converts f_3, f_5, f_6 to F3, F5 and F6 respectively. The 1024 switch for F3 sums 1000 Hz; for F5, 125 Hz; for F6, 512 kHz. Therefore:

$$F3 = f_3 \times \frac{1024}{1000}$$

$$F3 = \frac{(8192)(1.024)}{t_{on}\ (max)}$$

$$F5 = f_5 \times \frac{1024}{125}$$

$$F5 = \frac{(8.192)(1400)}{t_o\ (min)}$$

$$F6 = f_6 \times \frac{1024}{512 \times 10^3}$$

$$F6 = \frac{f_3 \left| T_1 - T_2 \right|}{2}$$

$$F6 = 0.512\ F3 \left| T_1 - T_2 \right|$$

When the control torque, T_c, vehicle inertia, I_V, and separation of inner and outer threshold, θ_c, has been selected, and the front panel scaled, the nominal gain required in the computation of t_{on} can be determined. This is illustrated below.

$$\text{Gain} = \frac{I_V\ \theta_c}{T_c} = \frac{t_{on}\ (t_i + t_o)\ t_o t_c}{t_c(t_i + 2t_o + t_c) + (t_i + t_o)t_o}$$

$$\text{Gain (scaled)} = \frac{2\left(\frac{t_{on}}{t_{on\,(max)}}\right)\left(\frac{t_i + t_o}{t_i\,(max)}\right)\left(\frac{t_o\,t_c}{t_o\,(max)\;t_o\,(max)}\right)}{\left(\frac{t_c}{t_o\,(max)}\right)\left(\frac{t_i + 2\,t_o + t_o}{t_i\,(max)}\right) + \left(\frac{t_i + t_o}{t_i\,(max)}\right)\left(\frac{t_o}{t_o\,(max)}\right)}$$

$$= \frac{I_V\,\theta_c}{T_c} \quad \frac{2}{t_{on}\,(max)\;t_o\,(max)}$$

$$= \frac{I_V\,\theta_c}{T_c} \quad 2\,\frac{(f_3\,f_5)}{(8192)^2}$$

To convert the gain to count

$$\text{Gain} = \frac{I_V\,\theta_c}{T_c}\left[\frac{2\;(f_3\,f_5)}{(8192)^2} \times 8192\right]$$

Therefore

$$\text{Gain} = \frac{I_V\,\theta_c}{T_c}\left[\frac{2F3\;\;F5}{(1.024)(8.192)(8192)}\right] \text{ count}$$

where 8192 counts = 8×10^{-3} seconds

$$\text{or}\;\; 1 \text{ count} = \frac{1}{1.024 \times 10^{6}} \text{ seconds}$$

SCALING MECHANICS

This section outlines the recommended procedure for the calculation of the Adaptive Attitude Control Computer scaling parameters and the start-up procedure with the Adaptive Attitude Control Computer interfaced with an analog computer. See Appendix for an alternate scaling technique.

Scaling Parameter Calculations (Fixed Dynamic Range)

1. Choose the following variables: I_V, θ_{db}, τ_1, τ_2, where

$$100 \leq I_V, \leq 5000 \text{ slug-ft}^2$$

$$0.1 \leq \left| \theta_{db} \right| \leq 1.0 \text{ degree}$$

$$0 \leq \tau_1 \leq 3.0 \text{ seconds}$$

$$0 \leq \tau_2 \leq 3.0 \text{ seconds}$$

2. Calculate the following variables

$$t_o\,(\text{min}) = \left\{ 2 - \left[4 - \left| \frac{2\theta_c}{\theta_{db}} \right| \right]^{1/2} \right\} x \left| \left\{ \frac{\theta_{db} I_V}{T_b\,(\text{max})} \right\} \right|^{1/2} \quad \text{sec}$$

where $\theta_c = 0.36\,\theta_{db}$; $T_b\,(\text{min}) = 5.85 \times 10^{-6}$ ft-lb; $T_b\,(\text{max}) = 2 \times 10^{-4}$ ft-lb

$$t_o\,(\text{max}) = \frac{(8192)\, t_o\,(\text{min})}{1400}$$

$$T_c = \frac{1.5\, I_V\, \theta_c}{t_{on}\,(\text{min})\, t_o\,(\text{max})}$$

where

$$t_{on}\,(\text{min}) = 3\,\tau_1 \geq 0.3 \text{ sec}$$

$$\text{for } \tau_1 = \tau_2$$

or

$$t_{on}\,(\text{min}) = 3\ \tau_1 + \left|\tau_2 - \tau_1\right| \geq 0.3\ \text{sec}$$

for $\tau_1 < \tau_2$

or

$$t_{on}\,(\text{min}) = 3\ \tau_1 - \left|\tau_2 - \tau_1\right| \geq 0.3\ \text{sec}$$

for $\tau_1 > \tau_2$

$$t_{on}\,(\text{max}) = 10\ t_{on}\,(\text{min}) \geq 4.096\ \text{sec}$$

3. Calculate the following scaling parameters

$$F3 = \frac{(8192)(1.024)}{t_{on}\,(\text{max})} \qquad \text{(count)}$$

$$F5 = \frac{(8.192)(1400)}{t_o\,(\text{min})} \qquad \text{(count)}$$

$$F6 = 0.512\ F3\ \left|\tau_1 - \tau_2\right| \qquad \text{(count)}$$

$$\text{Gain} = \frac{I_V\,\theta_c}{T_c} \times \left[\frac{2F3 \times F5}{(8.192)(8192)(1.024)(1.024)}\right] \qquad \mu\ \text{sec}$$

$$\text{Logic Threshold Gain} = \frac{5\ \text{volts}}{\theta_{db}\,(\text{deg})} \times \frac{1\ \text{deg}}{25\ \text{volts}}$$

Maneuver and Acquisition Threshold Gain =

$$\frac{5\ \text{volts}}{1.25\ \theta_{db}\,(\text{deg})} \times \frac{1\ \text{deg}}{25\ \text{volts}}$$

4. From Figures 23, 24, and 25 chose F1 count for desired target depth, logic threshold potentiometer turns and Maneuver and Acquisition threshold potentiometer turns respectively.

Start-Up Procedure

1. Turn logic and Maneuver and Acquisition threshold potentiometers to zero.

2. Apply power to circuit boards and allow 30 minutes for warm-up time.

3. Measure power supply voltages using E3 Buss as reference.

   E6 Buss Voltage = +4.8; +0, -0.10 vdc

   E8 Buss Voltage = +4.8; +0, -0.10 vdc

   E10 Buss Voltage = +12.00, ± 0.02 vdc

   E12 Buss Voltage = -12.00, ± 0.02 vdc

4. Establish control torque, T_1, T_2, maximum bias torque and RMS noise for the problem on the analog computer.

5. Set predetermined Maneuver and Acquisition threshold potentiometer turns on the Adaptive Attitude Control Computer with logic threshold potentiometer at zero.

6. Turn analog computer to Operate and allow Maneuver and Acquisition system to obtain a minimum impulse limit cycle in the presence of the maximum bias torque.

7. Adjust Maneuver and Acquisition threshold potentiometer such that the minimum impulse establishes a parabolic position limit cycle with a depth that crosses zero position.

8. Return analog computer to Reset.

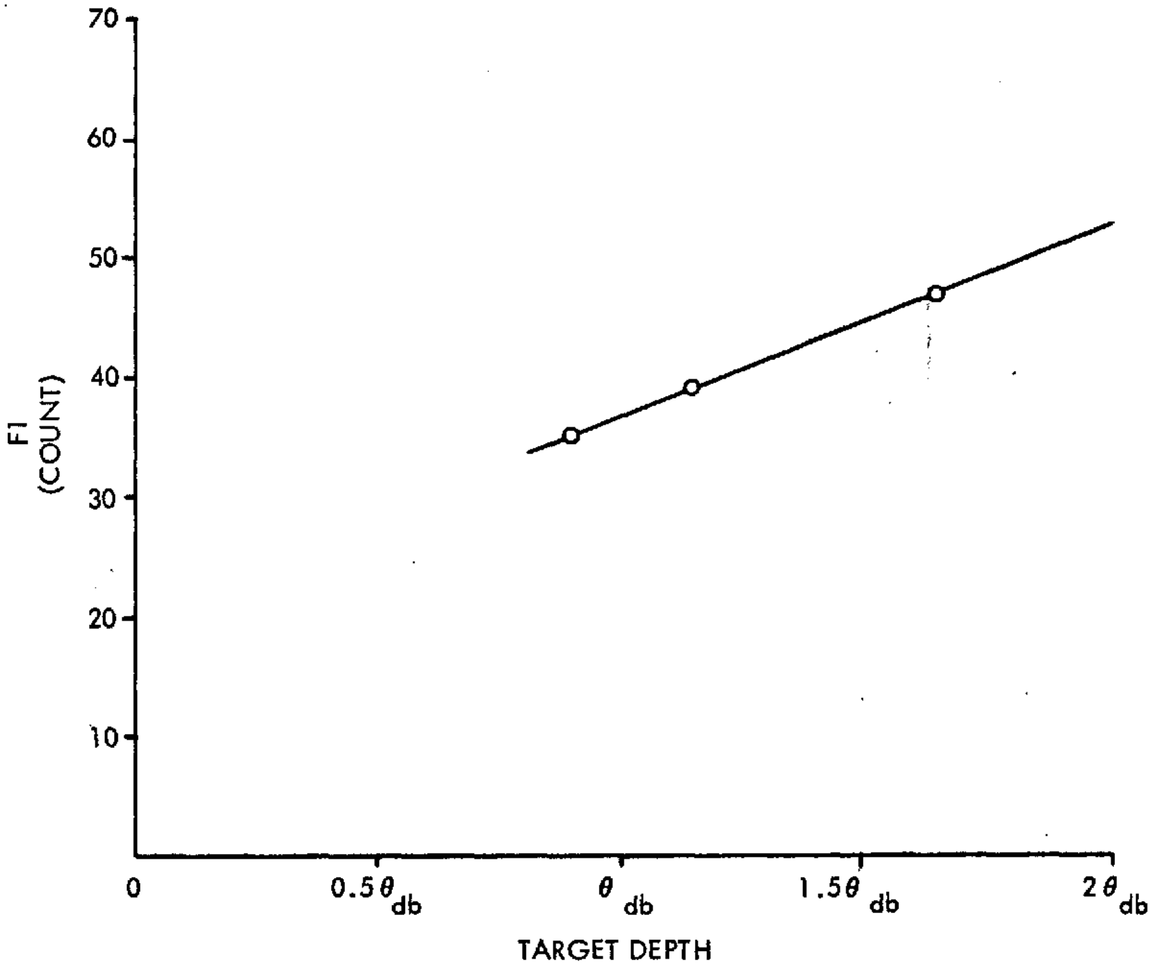


Figure 23. Nominal Target Depth Versus F1 Count

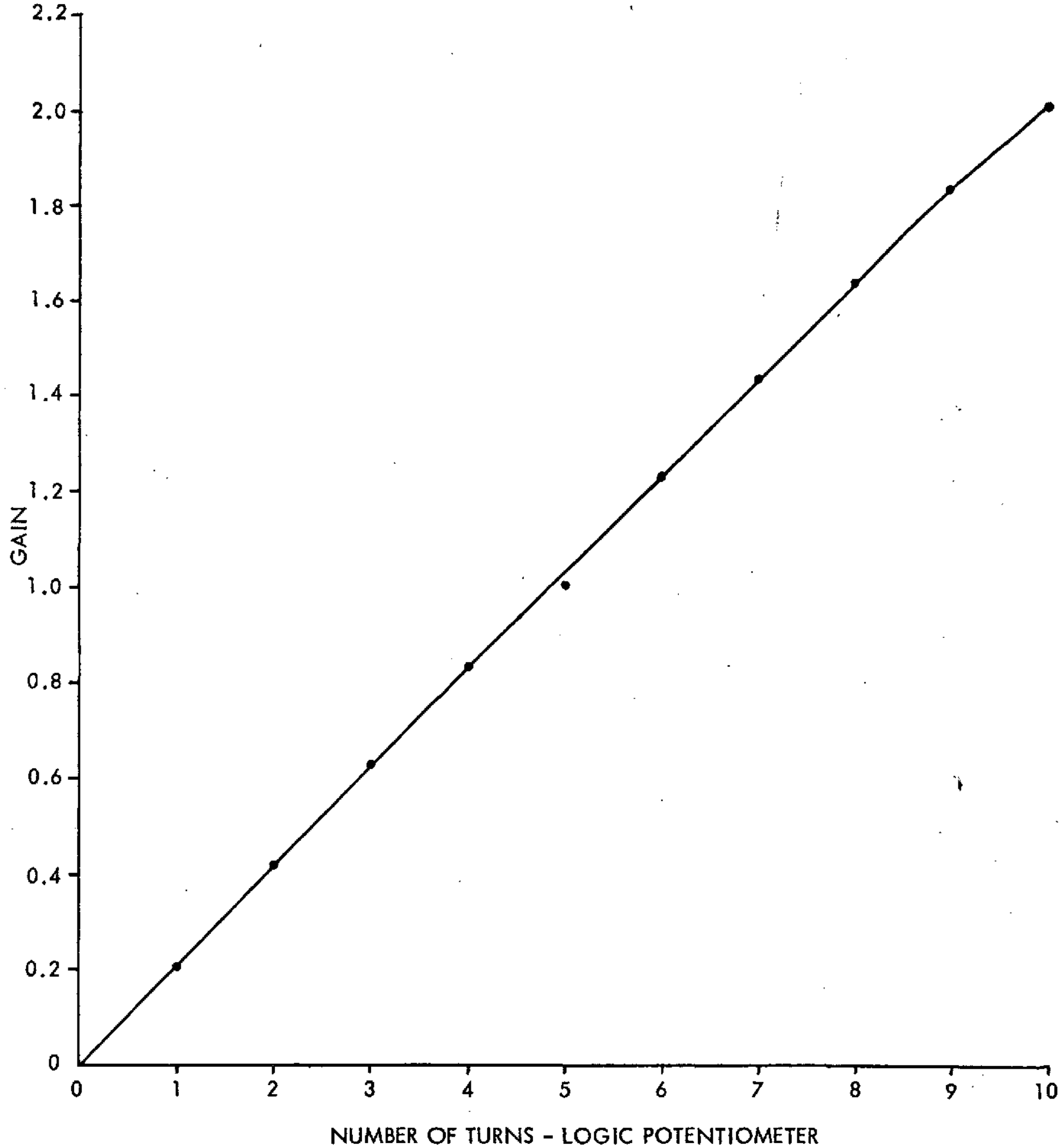


Figure 24. Logic Threshold Gain Versus Potentiometer Turns

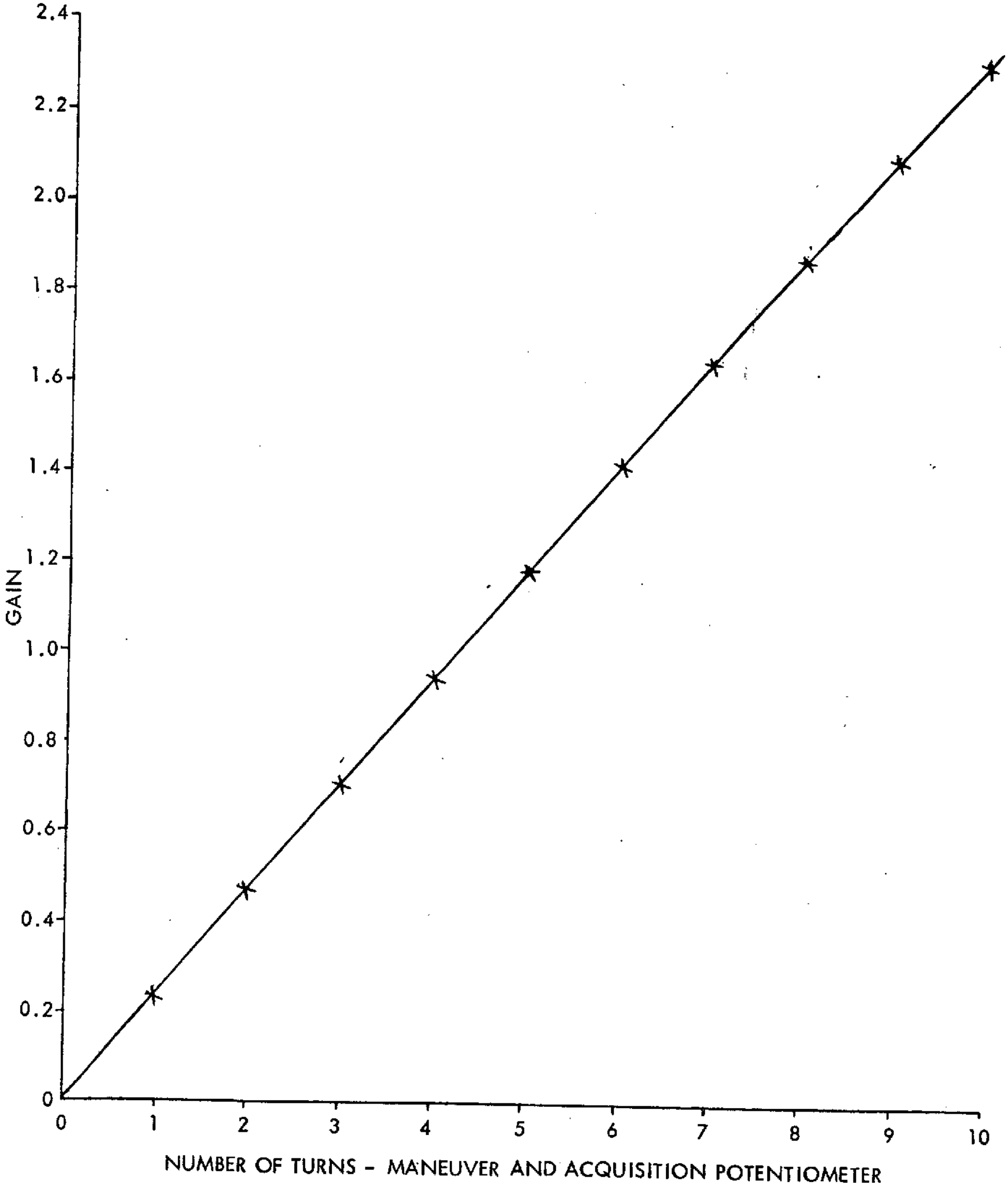


Figure 25. Maneuver and Acquisition Threshold Gain Versus Potentiometer Turns

9. Establish initial conditions of control torque, τ_1, τ_2, bias torque, rms noise, vehicle rate and position on the analog computer. The initial vehicle position must be greater than $|\theta_{db}|$.

10. Set predetermined logic threshold potentiometer turns; F1, F3, F5, F6 count switches; and $\tau_1 < \tau_2$ switch on Adaptive Attitude Control Computer.

11. Sequence initial vehicle position from $+\theta_o$ to $-\theta_o$ to $+\theta_o$ to start with a positive vehicle position or from $-\theta_o$ to $+\theta_o$ to $-\theta_o$ to start with a negative vehicle position. After a sequence from plus to minus or minus to plus, wait until the adaptive thruster on-time has been computed and the thruster has fired.

12. Insert the predetermined gain (μsec) measured between the ground test point and the axis gain test point by setting the gain count switch to 64, or 1024, and then, Preset, Reset and Insert using switches respectively labeled.

13. Turn analog computer to Operate.

14. After parabolic limit cycle has stabilized, adjust F1 to produce desired depth. (Increase F1 to increase target depth.)

15. Stop problem by returning analog computer to Reset.

16. Re-start problem by repeating steps 11, 12, and 13.

Example Problem

1. Choose:

$$I_V = 1000 \text{ slug-ft}^2$$
$$\theta_{db} = 0.1 \text{ degree}$$
$$\tau_1 = 0.1 \text{ second}$$
$$\tau_2 = 0.5 \text{ second}$$

where $T_b\ (\max) = 2.0 \times 10^{-4}$ ft-lb

$T_b\ (\min) = 5.85 \times 10^{-6}$ ft-lb

$\theta_c/\theta_{db} = 0.36$

2. Calculate variables

$$t_o\ (\min) = \left\{ 2 - \left[4 - 0.72\right]^{1/2} \right\} \left| \left\{ \frac{(1.745)(10^{-3})(1000)}{2 \times 10^{-4}} \right\}^{1/2} \right|$$

$$= 0.189\ (0.934)(10^2) = 17.65 \text{ seconds}$$

$$t_o\ (\max) = \frac{(8192)\ (17.65)}{1400} = 103.3$$

$$t_{on}\ (\min) = 0.3 + \left| 0.5 - 0.1 \right| = 0.7 \text{ second}$$

$$t_{on}\ (\max) = (10)(0.7) = 7 \text{ seconds}$$

$$T_c = \frac{(1.5)\ (1000)\ (0.36)\ (1.745)\ (10^{-3})}{(0.7)\ (103.3)} = 13.03 \times 10^{-3} \text{ ft-lb}$$

3. Calculate scaling parameters

$$F3 = \frac{(8192)(1.024)}{7} = 1198 \text{ count}$$

$$F5 = \frac{(8.192)(1400)}{17.65} = 657 \text{ count}$$

$$F6 = (0.512)(1198)(0.4) = 245 \text{ count}$$

$$\text{Gain} = \frac{(1000)(0.36)(1.745)(10^{-3})}{(13.03)(10^{-3})} \left[\frac{(2)(1198)(657)}{(8.192)(8192)(1.024)^2} \right]$$

$$= 1078\ \mu \text{ sec}$$

$$\text{Logic threshold gain} = \frac{5\,V}{0.1\,deg} \times \frac{1\,deg}{25\,V} = 2\ (\text{gain})$$

$$\text{Maneuver and Acquisition threshold gain} = \frac{5\,V}{(1.25)(0.1)\,deg} \times \frac{1\,deg}{25\,V} = 1.6\ (\text{gain})$$

4. Front Panel Settings

Logic threshold potentiometer turns - 10.0

Maneuver and Acquisition threshold potentiometer turns - 6.8

F1 nominal = 46

Count*	1024	512	256	128	64	32	16	8	4	2	1
F5 = 657		X		X			X				X
F1 = 46						X		X	X	X	
F3 = 1198	X			X		X		X	X	X	
F6 = 245				X	X	X	X		X		X

* The "X" indicates the corresponding switch should be in the up position

Set thruster time constant switch to $T_1 < T_2$ position.

FINE ADJUSTMENTS

While all required nominal parameter scaling and adjustments are made on the front panel of the Adaptive Attitude Control Computer, internal adjustment potentiometers are also included for adjusting threshold and hysteresis levels. These trim potentiometers are mounted along the top edges of the circuit cards involved, and are therefore easily accessible for adjustment after the top cover has been removed. In each case, the location of the desired adjustment potentiometer is located by referring to the assembly drawing of the circuit card given in the following instructions. The potentiometer symbol and location is shown on these drawings.

The functions which can be adjusted by these internal trim potentiometers are as follows.

- Control logic inner and outer threshold levels.
- Hysteresis levels of control logic inner and outer thresholds.
- Threshold levels of the lead-lag subsystems.
- Peak levels of the exponential hysteresis signals of the lead-lag subsystem.

The procedure for measurement and adjustment of these functions is as follows:

CONTROL LOGIC INNER AND OUTER THRESHOLDS AND HYSTERESIS

Circuit Card Schematic	854D320
Assembly	177F243

Positive Outer Threshold

Range of threshold adjustment: ≈ 3.7 to 6.2 vdc
Range of hysteresis adjustment: ≈ 0.2 to 1.1 vdc

a. Ground test points TP11 and TP15.

b. Adjust potentiometer R17 to give $-V_{(threshold)}$ at TP17. This is presently set at -5.00 ± 0.02 vdc.

c. Adjust potentiometer R30 to give $+V_{(hysteresis)}$ at TP14. This is presently set at +0.25 ± 0.02 vdc.

d. Remove ground from TP11 and TP15.

Positive Inner Threshold

Range of threshold adjustment: ≈ 2 to 5.1 vdc.
Range of hysteresis adjustment: ≈ 0.2 to 1.1 vdc.

a. Ground test points TP9 and TP12.

b. Adjust potentiometer R23 to give $-V_{(threshold)}$ at TP13. This is presently set at -3.20 ± 0.02 vdc.

c. Adjust potentiometer R39 to give $+V_{(hysteresis)}$ at TP10. This is presently set at +0.25 ± 0.02 vdc.

d. Remove ground from TP9 and TP12.

Negative Inner Threshold

Range of threshold adjustment: ≈ -2.2 to -6.2 vdc.
Range of hysteresis adjustment: ≈ 0.2 to 1.1 vdc.

a. Ground test points TP3 and TP6.

b. Adjust potentiometer R44 to give the desired $+V_{(hysteresis)}$ at TP4. This is presently set at +0.25 ± 0.02 vdc.

c. Adjust potentiometer R47 to give the sum of the voltages at TP4 and TP5 equal to $-V_{(threshold)}$. This is now set at +3.20 ± 0.02 vdc.

d. Remove ground from TP3 and TP6.

Negative Outer Threshold

Range of threshold adjustment: ≈ -3.9 to -7.3 vdc.
Range of hysteresis adjustment: ≈ +0.2 to 1.1 vdc.

a. Ground test points TP2 and TP8.

b. Adjust potentiometer R69 to give the desired $+V_{(hysteresis)}$ at TP7. This is presently set at +0.25 ± 0.02 vdc.

c. Adjust potentiometer R58 to give the sum of the voltages at TP1 and TP7 equal to $-V_{(threshold)}$. This is presently set at +5.00 ± 0.02 vdc.

LEAD-LAG SUBSYSTEM THRESHOLDS

Circuit Card Schematic	854D321
Assembly	177F242

The nominal threshold level is +5 vdc. Measure the voltage at TP2. This voltage should be -5.00 ± 0.02 vdc. Adjustment of this voltage is made by potentiometer R23.

LEAD-LAG SUBSYSTEM HYSTERESIS (EXPONENTIAL DECAY)

The exponential decay hysteresis is included in the lead-lag subsystem to provide control of the minimum impulse bit. Multiple pulsing due to sensor noise is also minimized. The hysteresis voltage is given by the equation:

$$V_{(hysteresis)} = V_0 e^{-\frac{t}{2}}$$

where V_0 is variable between 3 and 7 vdc.

Potentiometers R30 and R61 are provided for adjusting V_0 for the plus and minus thresholds, respectively.

Adjustment of V_0 is a function of sensor noise as well as vehicle dynamics and therefore is properly set under dynamic system conditions. The procedure for adjustment is as follows:

a. With the control logic deadband potentiometers set to zero (front panel), set Maneuver and Acquisition potentiometers to desired deadband levels.

b. Select desired sensor noise level in the analog computer along with other control system parameters.

c. Allow the lead-lag subsystems to acquire the limit cycles in each axis under maximum bias torque conditions.

d. Adjust potentiometers R30 and R61 so that approximately half the deadband is traversed in a scallop limit cycle with minimum multiple-pulsing.

The adjustments of these potentiometers have nominally been set under conditions of a signal-to-noise ratio of five-to-one (rms white noise, band-limited at 35 Hz), lead-lag position deadband of 125 percent of the control logic deadband, and 2×10^{-4} ft-lb of bias torque.

APPENDIX

SCALING PARAMETER CALCULATIONS (VARIABLE RANGE)

The Adaptive Attitude Control Computer scaling technique is outlined below for the case where the values for vehicle inertia, I_V; attitude deadband, θ_{db}; thruster time constants, T_1 and T_2; control torque, T_c; and maximum bias torque T_b (max); are predetermined and given as fixed mission parameters. The scaling variable for this case becomes the bias torque range of operation of the computer. The recommended scaling technique presented in the text assumes that the control torque can be selected to obtain the maximum bias torque range of operation or dynamic range.

The dynamic range can be expressed as a ratio of the maximum and minimum time measurement, t_o, and the count representing these measurements.

$$\frac{t_o\ (\text{max})}{t_o\ (\text{min})} = \frac{8192}{\text{Minimum Count}}$$

The minimum count for this alternate technique will not be fixed at 1400 as given in Section IV of this report, but will be determined by the required minimum thruster on time and the value of control torque. The effectiveness of this scaling approach will be dependent on the mission bias torque profile.

SCALING MECHANICS (VARIABLE DYNAMIC RANGE)

1. Given the mission parameters of

$$I_V,\ \theta_{db},\ T_1,\ T_2,\ T_c \text{ and } T_b\ (\text{max})$$

2. Calculate

$$t_o\,(\text{min}) = \left\{ 2 - \left[4 - \left| \frac{2\theta_c}{\theta_{db}} \right| \right]^{1/2} \right\} \times \left| \left\{ \frac{\theta_{db} I_V}{T_b\,(\text{max})} \right\} \right|^{1/2} \quad \text{sec}$$

$$t_o\,(\text{max}) = \frac{1.5\, I_V\, \theta_c}{t_{on}(\text{min})\, T_c}$$

where

$$t_{on}\,(\text{min}) = 3\, T_1$$

$$\text{for } T_1 = T_2$$

or

$$t_{on}(\text{min}) = 3\, T_1 + \left| T_2 - T_1 \right|$$

$$\text{for } T_1 < T_2$$

or

$$t_{on}(\text{min}) = 3\, T_1 - \left| T_2 - T_1 \right|$$

$$\text{for } T_1 > T_2$$

$$t_{on}(\text{max}) = 10\, t_{on}\,(\text{min}) \geq 4.096 \text{ sec}$$

(Increase in t_{on} (max) will be required for an increase in dynamic range.)

$$\text{Minimum Count} = \frac{8192 \times t_o\,(\text{min})}{t_o\,(\text{max})}$$

3. Calculate the following scaling parameters

$$F3 = \frac{(8192)\,(1.024)}{t_{on}\,(\text{max})} \qquad \text{Count}$$

$$F5 = \frac{(8.192)\ (\text{Minimum Count})}{t_o\ (\text{min})} \qquad \text{Count}$$

$$F6 = 0.512\ F3\ \left| T_1 - T_2 \right| \qquad \text{Count}$$

$$\text{Gain} = \frac{I_V\ \theta_c}{T_c} \times \left[\frac{2F3 \times F5}{(8.192)\ (8192)\ (1.024)^2} \right] \qquad \text{u sec}$$

$$\text{Logic Threshold Gain} = \frac{5 \text{ volts}}{\theta_{db}(\text{deg})} \times \frac{1 \text{ deg}}{25 \text{ volts}}$$

Maneuver and Acquisition Gain =

$$\frac{5 \text{ volts}}{1.25\ \theta_{db}(\text{deg})} \times \frac{1 \text{ deg}}{25 \text{ volts}}$$

4. From Figures 23, 24 and 25 choose F1 count for desired target depth, logic threshold potentiometer turns, and Maneuver and Acquisition Threshold potentiometer turns respectively.

EXAMPLE PROBLEM

1. Given

I_V	=	1600 slug - ft^2
θ_{db}	=	0.1 degree
$T_1 = T_2$	=	0.033 sec
T_c	=	0.08 ft-lb
T_b (max)	=	2×10^{-4} ft-lb
θ_c / θ_{db}	=	0.36

2. Calculate Variables

$$t_o\ (\min) = \left\{ 2 - \left[4 - 0.72 \right]^{1/2} \right\} \left\{ \frac{(1.745)\ (10^{-3})\ (1600)}{(2)\ (10^{-4})} \right\}^{1/2}$$

$$= 22.32 \text{ sec}$$

$$t_{on}\ (\min) = (3)\ (.033) = 0.1 \text{ sec}$$

$$t_{on}\ (\max) = (0.1)\ (10) = 1 < 4.096$$

$$\therefore\ t_{on}\ (\max) = 4.096 \text{ sec}$$

$$t_o\ (\max) = \frac{(1.5)\ (1600)\ (0.36)\ (1.745)\ (10^{-3})}{(0.1)\ (0.08)} = 188.5 \text{ sec}$$

$$\text{Minimum Count} = \frac{(8196)\ (22.32)}{188.5} = 970$$

3. Calculate Scaling Parameters

$$F3 = \frac{(8192)\ (1.024)}{4.096} = 2048$$

$$F5 = \frac{(8.192)\ (970)}{22.32} = 356$$

$$F6 = 0$$

$$\text{Gain} = \frac{(1600)\ (0.36)\ (1.745)\ (10^{-3})}{0.08} \times \left[\frac{(2)\ (2048)\ (356)}{(8.192)\ (8192)\ (1.024)^2} \right] = 260 \text{ u sec}$$

$$\text{Logic Threshold Gain} = \frac{5}{0.1} \times \frac{1}{25} = 2.0$$

$$\text{Maneuver and Acquisition Gain} = \frac{5}{0.125} \times \frac{1}{25} = 1.6$$

EXAMPLE PROBLEM

Assume same values of I_V, θ_{db}, T_c, θ_c/θ_{db} and T_b (max) as previous problem. Changing the value of T_1 and T_2 will illustrate the change in dynamic range (Minimum Count).

1. Given $T_1 = 0.1$ $T_2 = 0.2$

2. Calculate Variables

$$t_o \text{ min} = 22.32 \text{ sec}$$

$$t_{on}(\text{min}) = (0.1)(3) + 0.1 = 0.4 \text{ sec}$$

$$t_{on} \text{ max} = 4 \text{ sec} < 4.096$$

$$t_{on}(\text{max}) = 4.096 \text{ sec}$$

$$t_o(\text{max}) = \frac{(1.5)(1600)(1.745)(10^{-3})(0.36)}{(0.4)(0.08)} = 47.11 \text{ sec}$$

$$\text{Minimum Count} = \frac{(8192)(22.32)}{47.11} = 3881$$

3. Calculate Scaling Parameters

$$F3 = \frac{(8192)(1.024)}{4.096} = 2048$$

$$F5 = \frac{(8.192)(3881)}{22.32} = 1424$$

$$F6 = (0.512)(2048)(0.1) = 104$$

$$\text{Gain} = \frac{(1600)(0.36)(1.745)(10^{-3})}{0.08} \times$$

$$\left[\frac{(2)(2048)(1424)}{(8.192)(8192)(1.024)^2}\right] = 1041 \; \mu \text{ sec}$$